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# The Structural Evolution of the Broken Hill Pb-Zn-Ag Deposit, New South Wales, Australia.

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by

*Edward*

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*CODES*



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*To Nancy and Mannie*

***FOR THE GROWING GOOD OF THE WORLD IS PARTLY DEPENDENT  
ON UNHISTORIC ACTS; AND THAT THINGS ARE NOT SO ILL WITH  
YOU AND ME AS THEY MIGHT HAVE BEEN, IS HALF OWING TO THE  
NUMBER WHO LIVED FAITHFULLY A HIDDEN LIFE, AND REST IN  
UNVISITED TOMBS.***

*George Elliot "Middlemarch"*



## DECLARATION

This thesis contains no material which has been accepted for a degree or a diploma by the University, or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of the author's knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis.



.....  
A. E. Webster, July 2004.

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## ABSTRACT

Broken Hill Type lead-zinc-silver deposits (BHT) are a sought after style of mineralisation because of their simple metallurgy and high metal grades. The purpose of this research project is to gain a deeper understanding of the complex BHT style of mineralisation through a comprehensive re-examination of the structure and stratigraphy of the 300 million tonne, multiply deformed and metamorphosed, type example, located at Broken Hill, in far western New South Wales, Australia. This study used the techniques of structural analysis of high-grade gneiss terrains and exploited 119 years of geological data collected during the mining exploitation and exploration of the Broken Hill (BH) mining field. The gneissic sulphide-silicate-carbonate rocks of the BH ore environment lend themselves well to such structural studies because of their mineralogical diversity, coarse grain-size and because of the presence of distinctive and persistent marker units. The result is a deposit-scale stratigraphic and structural model of this complex mineralised system, which allows an unparalleled view of the 'anatomy' of this giant deposit.

The Palaeoproterozoic BH mineralised system is a stratified complex that contains at least nine separate economically significant mineralised horizons, known as 3 Lens (lowest); 2 Lens; 1 Lens Lower; 1 Lens Upper (southern 1 Lens); A Lode Lower (Southern A Lode); A Lode Upper and B Lode. It is hosted within a sequence of metasedimentary and metavolcanic rocks, and coeval intrusives, known as the Willyama Supergroup, a multiply deformed upper amphibolite to granulite facies gneiss terrane. The deposit lies at the southwestern end of a lens of quartzofeldspathic and mafic rocks on the boundary between the Thackaringa and Broken Hill Groups. The quartzofeldspathic and mafic rocks are interpreted to be a metamorphosed volcanic complex.

A distinctive Mine Sequence hosts the orebodies and their distal equivalents and has been identified over a 25-kilometre strike length. It is a continuous sequence from the basal Footwall Quartzofeldspathic Gneiss to the Hangingwall Quartzofeldspathic Gneiss (interpreted to be an intrusive), but has considerable stratigraphic complexity. It can be subdivided into a Footwall Succession, Lode Sequence (host to the mineralisation) and a Hangingwall Succession. The Lode Sequence can be further subdivided into several lode rock units and associated metasediments in the southwestern and central parts of the field, including the '4.5' Horizon; the Upper Potosi Type Quartzofeldspathic Gneiss; the B Lode Horizon and the Garnet Quartzite Horizon. In the near-ore position, the Footwall Succession is represented by the 'underwall zone', which is distinguished by a marked thinning of key horizons and interbedded clastic metasediments. Manganiferous garnet-rich rocks of various types and textures are associated with the main orebodies, as are calc-silicate-rich horizons, magnetite-bearing metasediments, thin "banded iron formation", and mineralised psammite.

The orebodies and their wall rocks have been affected by two major periods of regional metamorphism (M1 and M2). M1 coincided with the Olarian Orogeny and two protracted deformational events; D2 and D3, which commenced at or immediately prior to the peak of metamorphism. D2 took place at the culmination of M1 and D3 as it waned. Most deformation of the mineralised system took place during D2 and the first phase of D3 (D3A). D1 is only represented in the Mine Sequence by a pervasive S1 schistosity and by pegmatite dykes and melt segregations. M2 coincided with the

Delamerian Orogeny and D4. Only a single phase of granulite to upper amphibolite grade regional metamorphism is recognised in the BH area.

High grade, south verging, asymmetric F2 folds comprise all of the significant macroscopic folds in the Mine Sequence and cause much of the present orebody geometry. They are parasitic to, and lie within the north limb of, a major regional F2 antiform; the Airport Antiform. The intensity of F2 folding is greater in the northeastern end of the field and is associated with a pervasive galena-defined S2 axial plane foliation in 3 Lens and 2 Lens. Folding and transposition equally affected both ore and adjoining wall rocks. S0 banding and syn-depositional stratigraphic variations within the orebodies are folded around F2 axes and modified by syn-D2 mobilised sulphides. F2 folds also deform a well-defined layering in 2 Lens, B Lode and A Lode Lower. All significant fluid phase sulphide mobilisation, and most mechanical sulphide mobilisation, took place within the orebodies during D2 and D3A.

There is continuity from D2 folding to early retrograde (granulite to upper amphibolite grade) D3A ductile shearing and attenuation. D3A shearing extensively modified the folded geometry of the mineralised system, dislocating and attenuating F2 folds and producing a series of deposit-wide, anastomosing shear arrays in which narrow (<15m), but intense D3A shears traverse the Lode Sequence at acute angles. D3A shears have a north block up, sinistral sense of movement, with horizontal displacements of up to 350 metres and the effects of shearing were particularly focussed in F2 fold limbs, and synformal keels that contained large masses of metasediment-hosted ore. D3A shears contain localised occurrences of mesoscopic F3 folds with a well-defined sillimanite biotite axial plane fabric (S3), and planes of intense transposition. Each successive stage of D3 is characterised by progressively lower grade metamorphic mineral assemblages in ore and wall rocks, and the styles of deformation reflect decreasing ductility. The differing styles of deformation are interpreted to reflect stages in the waning of M1. D3B shearing is characterised by a lower amphibolite to greenschist grade mineralogy, and is recognised as belts of quartz-muscovite-biotite schist that are mainly focussed in areas strongly deformed during D3A. The effects of D3B are not evenly distributed in the mining field and the northeastern part of the deposit has been particularly influenced by these structures.

M2 affected the orebodies during the Delamerian Orogeny and locally exceeded greenschist grade. M2 was associated with a fourth period of deformation (D4). Within the orebodies, it caused the re-activation of Olarian D3A-D3B shears and produced a generation of brittle fault systems. Transgressive dolerite dykes intruded the ore system in three main belts. There were at least two distinct phases in D4, an earlier, relatively high-grade phase, D4A, which reached lower amphibolite grade in places and with locally higher grades in faults associated with hydrothermal activity, and a subsequent D4B phase, which was possibly a distinct reactivation event. D4A was associated with localised ductile deformation, in the form of F4 folds, and caused the major reversal in F2 plunges in the central mining field. F4 folds are closely associated with complex fault zones, such as the British Fault System, and refold the main orebodies. Mechanical sulphide mobilisation dismembered dolerite dykes within 2L and 3L. Hydrothermal activity along D4 faults produced alteration within mineralisation, including sulphide mobilisation and impregnation on the margins of the dykes. D4 had particularly widespread effects in the northeastern part of the mines area, being mainly manifested as brittle-ductile to brittle deformation that is most commonly represented by the development of the extensive fault, joint and fracture

systems. D4 faults, dykes, folds and quartz-siderite galena veins overprint Olarian structures within the orebodies.

The elongate geometry, and the stratigraphy of the BH mineralised system predate all of the deformation that has affected the region and it preserves syn-depositional textures, internal stratification and layered gangue mineral distributions that predate D1 pegmatite intrusion. The stratigraphy of the mineralised complex is tectonically modified but the succession can still be readily discerned and the stratified orebodies and their associated 'lode rocks' are concordant with the surrounding stratigraphy. Structural fabrics have been formed in the ores and in their wall rocks during D2 to D4 and each of these events has affected D1 pegmatite intruded into the mineralisation and host sequence. F2 folds traverse the Lode Sequence stratigraphy, including the Garnet Quartzite Horizon and five orebodies retain a trend that is 20° clockwise of the F2 hinge orientation. D3 shear zones have subsequently accentuated the elongate form of the system. The effects of D3 shears have not been profound however, and they are confined to relatively narrow and discrete planes. There has not been any large or medium scale tectonic mobilisation of syngenetic mineralisation into structural sites during D2 and the ore has not been moved on a mass scale by deformation. The high aspect ratio of the mineralised system is interpreted to be a primary feature and the orebodies are still largely in their site of deposition, relative to the surrounding stratigraphy. The orebodies and most lode rocks were in place, as a series of strongly elongated, lenticular bodies of sulphide-silicate-calcite mineralisation and manganese-rich rocks prior to deformation and metamorphism. The relationships between the stratigraphy of the mineralised system and the structures that have modified its geometry show that the BH orebodies are a part of the sedimentary succession in which they lie, and have been deformed and metamorphosed along with the other rocks with which they are interlayered.

Empirical exploration models for BHT style mineralisation have been developed, based on the findings of this comprehensive re-examination.

## ACKNOWLEDGEMENTS

This project was commenced on a part-time basis in September 1995, while I was working as a geologist for Pasminco Mining-Broken Hill. This company is acknowledged for the initial in-kind support of the project and, following my departure from the company, for the continued access to mine data.

After leaving Pasminco in February 1997, my supervisors, Dr Ron Berry and Professor Ross Large, found the funds for me to continue the project on a full time basis over the next two and a half years. That period working at the Centre for Ore Deposit Research (CODES) and School of Earth Sciences, University of Tasmania was one of the most enjoyable and intellectually stimulating of my career. I can't thank them enough. While there, my office mates helped me to finally understand what a true learning environment is all about – arguments, ideas, fun and intellectual stimulation (and the odd beer or two). Thanks Rowdy, Wino, Holger and John.

In October 1999, I left Tasmania to return to the workforce and went back to part time status. This allowed the work to continue in Broken Hill. Ron Berry always made the effort to track me down to check on my progress, offered advice when needed, and sought me out when I had completely disappeared off the radar screen. Ron waded through a very early draft version of this thesis and then made the time to read all subsequent versions. The short, sharp doses of reality and the occasional kick up the backside were all appreciated. I would probably have given up long ago if I hadn't received the encouragement from Ron to complete it all. Professor Ross Large is acknowledged for embracing the findings of the study and incorporating this work into ongoing research into BHT deposits.

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Scott Stansfield, formerly of Pasminco Mining-Broken Hill, collected one of the garnet quartzite specimens used here, and recorded the geology of the locality. John Stockfeld provided many lessons in mineral identification. They are two of the best of the many good geologists who have worked on the Broken Hill mines. Without the many mine geo's such as them, this project could not have been undertaken.

It would have been impossible to even start this project without being able to see the geology of the orebodies through the eyes of others. Good geological recording and good record keeping in enduring data formats has made the Broken Hill mineralised system one of the best recorded in Australia. It is a model for other mining fields to follow, even in this digital age. The best exploration models are those that are based on well-recorded mineralised systems. Mine geologists document the geology of exploited mineralised systems and the best recorded are those that have been well described during mining. Mine geologists have done the most valuable work at Broken Hill, but their efforts have mostly lain unrecognised in mine records, and poorly acknowledged in the literature. I hope I have adequately acknowledged them here.

While decades of detailed geological data collection has been undertaken by company geologists at Broken Hill, the foundation stone was laid by three geologists; H. K. Gustafson, H. C. Burrell and M. D. Garretty, of the Central Geological Survey (1936-1939). Their work is probably one of the best investigations into a mining field ever completed in Australia. I wish I could have met them, to thank them personally.

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# CHAPTER 1: INTRODUCTION

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## 1.1 PREAMBLE.

The scientific literature contains few mineral deposit studies that have taken full advantage of the geological data that is routinely gathered in mining operations. Mines exploit mineral deposits and mining geologists collect vast quantities of information about these exploited mineralised systems during their day-to-day activities. In large mines and long-lived mining fields, geological data collection may extend over many decades. In this thesis it will be shown that if such information is analysed and incorporated into a comprehensive ore deposit study, detailed models of the geological architecture and structure of very complex mineralised systems can be produced. Such models will have a greater breadth and clarity than would otherwise be achievable by a more typical ore deposit study. Broken Hill, with a 119-year history of mining exploitation and geological interest, provides one of the best opportunities to show the value of a mine-data approach to ore deposit research.

The scientific literature also lacks mineral deposit studies in which the techniques of structural analysis of high-grade gneiss terrains (e.g. Hobbs, et al., 1976; Passchier, et al., 1990) have been applied to multiply deformed orebodies and in particular, the giant Broken Hill lead, zinc, silver deposit. During this study, from surface mapping and detailed lithological mapping have been undertaken within the mineralised rocks and in the surrounding wall rocks. An extensive mine geological archive has been re-examined in detail to provide additional raw data for a deposit-scale stratigraphic and structural compilation that provides a context for new observations. New observations can now be linked with geological features recorded in inaccessible parts of the deposit. Underground geological mapping has been particularly applicable to the present study because it has lent itself well to the structural emphasis of the project. Over 80% of the underground workings at Broken Hill are now (in 2002) inaccessible and many shallow parts of the deposit have been mined away by open cuts. So, the only way to gain a comprehensive understanding of the geological architecture of this immense mineralised system and its immediate environment, is to re-examine the unpublished mine records.

In high-grade gneiss terranes, "sequences of intrusion" into high-grade metamorphic rocks form much of the basis for the relative timing of deformational events (Passchier et al, 1990). Mineralised rocks such as the Broken Hill orebodies are no different to more typical gneisses and so during this project, new data about overprinting relationships within the deposit has been collected by detailed mapping of ore textural and gangue mineral types within the orebodies. New information about the relative timing of distinct and overprinting gangue mineral assemblages and textural types, sulphide textural types, overgrowths of new gangue mineral species (or recrystallisation of same species with a different texture or habit) and the recognition of a number of generations of sulphide-silicate veins have all been recorded in the underground workings and some surface exposures during the course of this study. A model for the structural development of the metamorphic rocks comprising the orebodies has been developed from the integration of such observations with the model of the geological architecture of this giant deposit constructed from mine data and new mapping.

To complete this research required a detailed knowledge of the Broken Hill orebodies, a familiarity with the rock types acquired over long-term observation within the accessible mining areas and remnant surface exposures; access to drill core and sampling data and a comprehensive understanding of the historic information from all of the former mines of the field. The author has achieved this during the course of the research. In the process, routinely gathered mine geological information has been adapted in new ways, to the needs of a detailed ore deposit study.

## 1.2 THE BROKEN HILL DEPOSIT.

The Palaeoproterozoic Broken Hill lead-zinc-silver deposit is located in the Barrier Ranges of far western New South Wales, Australia at latitude 31° 58' south, longitude 141° 28' east (Figure 1.1a). The deposit represents the type example of the "Broken Hill Type" (BHT) mineral deposits (King & Thomson, 1953; Beeson, 1990), one of the worlds most sought after styles of mineralisation. BHT's are sought after because they are often of very large tonnage, enriched in one or more of lead, zinc or silver and have simple metallurgy. The Broken Hill orebodies remain the largest and richest example of the type yet discovered. A brief account of the discovery of the deposit is presented in Appendix 2.



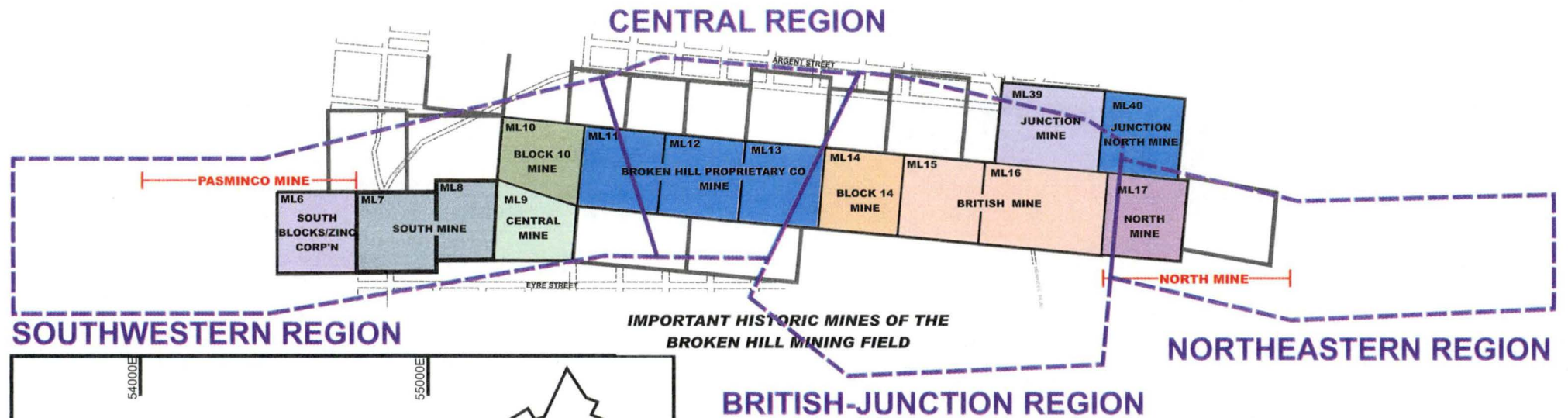


Figure 1.1b. Important historic mines of the central part of the Broken Hill mining field. Early mine names are used in the text to refer to geographic regions of the field.

The sub-zones of the Broken Hill mining field that are referred to in the text are shown in blue outline. These regions approximate structural domains and are discussed in Chapters 5 and 7.

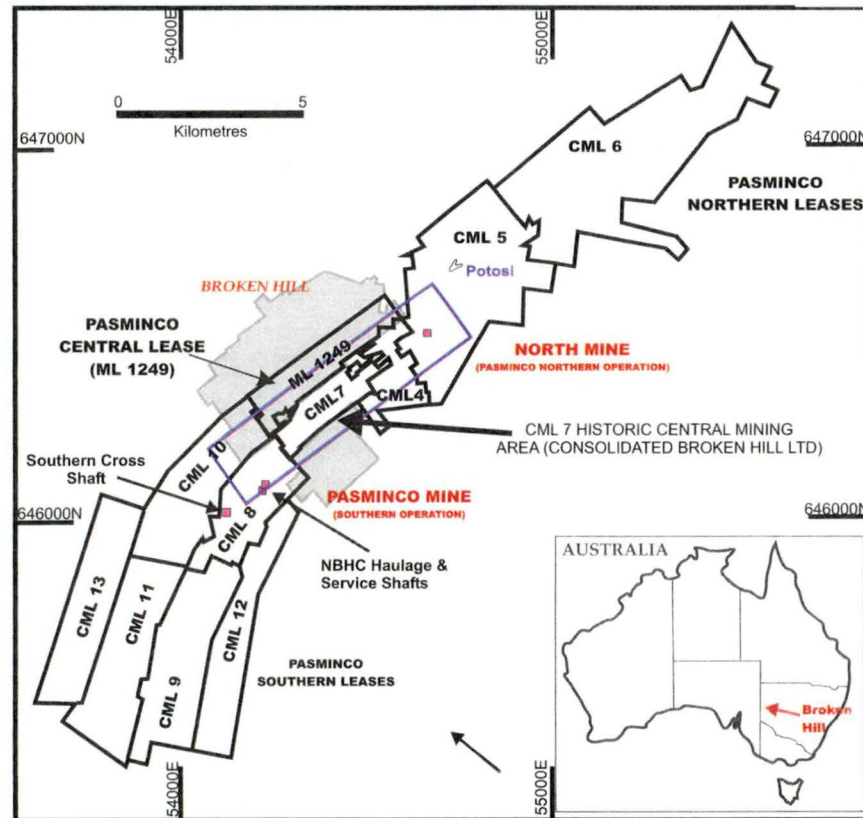


Figure 1.1a. Plan of the current consolidated mining leases of the Broken Hill mining field. The light grey area is the urban development of Broken Hill. For details of the former mining leases, refer to Figure 1.1b. The area of Figure 1.1b is outlined in blue.

Figure 1.1.

BHT's are geologically enigmatic and there is an ongoing debate about their origins and subsequent modification (e.g. King and O'Driscoll, 1953; Stillwell, 1959; Wright, Haydon and McConachy 1987; White et. al., 1995; Rothery, 2001). It is hoped that the research reported here will significantly add to the understanding of the type example and therefore this whole class of mineral deposit.

### 1.2.1 Tonnage and Grade of the Broken Hill Deposit.

The Broken Hill orebodies are a world-class accumulation of Pb-Zn-Ag, representing one of the largest, richest and metallurgically simple accumulations of these metals in the world. Mining commenced in 1883 and continues at present (2002) in the Pasminco Broken Hill Mine which remains Australia's second largest zinc-lead mine. In the early 1990's, economically mineable ore from the underground mines was required to exceed 10% combined lead and zinc but the cutoff grades in earlier times significantly exceeded this amount. So the deposit still produces some of the world's richest lead-zinc ores.

In 2001, 2.8 million tonnes of ore was still being produced annually, at an average grade of 10 percent combined lead and zinc (Pasminco Ltd., unpublished data 2002). In 2000, the following unmined resource remained in the Pasminco leases (Pasminco Ltd, Broken Hill resource statement , 31 March 2000).

	<b>Tonnes</b>	<b>Zn(%)</b>	<b>Pb(%)</b>	<b>Ag(g/t)</b>
<b>Resources</b>	20,200,000	9.0	5.0	52
<b>Reserves</b>	16,800,000	7.4	3.9	42

Between March 2000 and the March 2002 production has been 4.9 million tonnes at 7.3% Zn, 3.5% Pb and 39.1 g/t Ag. In 2000, 2.827 tonnes was mined to produce 184000 tonnes of zinc, 101000 tonnes of lead and 91000 kilograms of silver (Pasminco Ltd, unpublished data, 2002). Within the resource model there is 25.1 million tonnes of additional mineralisation at 12.0% Zn, 7.4% Pb and 61 g/t Ag at the Southern Operations. This mineralisation has previously been classified as resources but later downgraded because the prevailing cost structure had made it uneconomic to extract. It may become economic to mine in the future. So even after 119 years of mining, BH still ranks as one of the largest lead-zinc deposits in Australia.

Estimates of the original contained tonnage of the ore at Broken Hill vary. Haydon and McConachy (1987) estimated that there was originally 300 million tonnes of mineralised material exceeding 5% combined lead and zinc, of which 150 million tonnes exceeded 20% combined lead and zinc. Burton (1990) used past mining production figures and resource estimates to show that the Broken Hill deposit contained 279 million tonnes of ore before mining. R. Morland (unpublished data, 1993) calculated that a total of 175.8 million tonnes of ore had been mined prior to 1993 and 28.9 million tonnes remained *in situ*. Assuming that any mined material contained 10% dilution, he considered that 185 million tonnes of ore had been mined up to that date.

Between 1883 and 1994, the total metal production from the deposit was (Pasminco Ltd, unpublished data, 1995);

- 19.3 million tonnes of lead,
- 16.6 million tonnes of zinc,
- 28.7 million kilograms of silver,
- 23 tonnes of gold (a by product of base metal mining).

What is perhaps most surprising about the BH mineralised system is that its full extent is still unknown. While the southwestern end of the deposit was defined by Pasminco mine geologists in the 1990's to present and can be confidently closed off, the drilling at depth in the north-eastern end of the field, beyond the workings of the former North Mine, showed the orebodies remain open at depth. The last intersections of ore grade sulphides were obtained in the "2K" Zone to the northeast of the Western Shear and a body of ore grade sulphides of approximately 0.6 MT grading 18% Pb, 17% Zn and 350g/t Ag was defined prior to closure of the Pasminco Northern Operation in February 1993 (Pasminco Ltd, unpublished data, 1999). This zone is open at depth and the potential tonnage is unknown.

Previous workers have suggested that a significant tonnage of mineralisation has been lost from the deposit by erosion. However, as will be discussed Chapter 6, only 2,000,000 tonnes of high-grade ore and a similar amount of low-grade material has been lost from the orebodies due to erosion. So the BH mineralised system is essentially intact and a comprehensive study such as this can 'look' at the entire system.

### 1.2.2. Broken Hill Type Deposits.

Broken Hill Type deposits (BHT) form an economically important and unique category of base metal deposit (King & Thomson, 1953; Beeson, 1990; Parr and Plimer, 1993). BHT deposits have been described as having the following characteristics (Walters, 1996b);

1. A fundamental association with Palaeo-Mesoproterozoic mobile belt terranes
2. A direct relationship with “unusual” lithologies referred to as “exhalites”, such as thinly banded “iron formations” as well as a diverse suite of Fe-Si-Mn-Ca-rich lithologies with “skarn-like textures”,
3. All BHT terranes have undergone prolonged histories of complex deformation, metamorphism and metasomatism,

Key examples of the type include;

#### *Australia;*

- Broken Hill Domain (Broken Hill, Potosi, Pinnacles)
- Mt Isa Inlier (Cannington, Pegmont),

#### *South Africa;*

- Namaqua Belt (Gammsberg, Broken Hill (South Africa), Black Mountain, Big Syncline,

#### *Scandinavia;*

- Bergslagen District (Sweden) – (Zinkgruvan), (though with significant differences and it is uncertain whether these are true BHT's).

On the basis of a comparison of the Broken Hill deposit (NSW), Cannington (Qld), Zinkgruvan (Sweden), Aggeneys-Gammsberg (SA) and Sullivan (Canada), Walters (1996b) has defined the characteristics of BHT deposits (Figure 1.2).

### 1.3. THE PRESENT STUDY.

This investigation attempts to unravel the complex geology of the sulphide-silicate-carbonate rocks and distinctive companion lithologies that comprise the Broken Hill Pb-Zn-Ag deposit.

One of the purposes of the project is to assess whether the orebodies and their distinctive companion lithologies show evidence of having undergone the regional deformations that are recognised in the rocks of the district (eg. Laing et. al., 1978; White et. al., 1995). Examining the effects of regional deformation within the mineralised rocks and associated lithologies is considered essential to gaining an understanding of the genesis of this giant metal accumulation, given the wide-ranging genetic models that have been suggested by previous workers (eg. Andrews, 1922; Gustafson et al., 1950; King and Thomson, 1953 and Rothery, 2001). If all regional events are not represented in the mineralised rocks, then it would suggest that the deposit formed during, or after the event for which no evidence can be found. Conversely, if it can be shown that the mineralised rocks preserve evidence of all of the regionally recognised deformations, then the deposit must have been present before all deformational events.

If it can be shown that the mineralised rocks were present early in the geological history of the Broken Hill region, then it allows the possibility that pre-deformational geological features of the mineralised rocks could be preserved. This information may lead to accurate reconstructions of the depositional environment of the orebodies. Ultimately, such information and models could suggest a genetic mechanism for the Broken Hill mineralisation.

### **1.3.1 Aims of the Study.**

The purpose of this research project is to gain a deeper understanding of the complex BHT style of mineralisation through a comprehensive reassessment of the geology of the type example in Broken Hill, NSW, Australia. Specific aims of the study include;

1. To describe the geology of the orebodies and near-ore environment of the +8.5 kilometre long Broken Hill Zn-Pb-Ag deposit.
2. To synthesise a single coherent model of the structural evolution of the Broken Hill Pb-Zn-Ag deposit from the information preserved in the fabric of the orebodies and their wall rocks.
3. To describe the sequence of structural and metamorphic events which produced the current form of the deposit and to record the textural, mineralogical and geometrical changes that are related to each phase of its deformational history.
4. To develop a model of the pre-deformational form of the deposit and to suggest a depositional mechanism for the orebodies and their wall rocks.

To achieve the aims has required an integrated approach requiring the development of techniques by which the mass of existing mine data could be more completely utilised than in previous studies. The techniques employed are outlined in Appendix 3 and 6.

This study differs from previous investigations because of a focus on the effects of structural and metamorphic events on the calc-silicate-carbonate-silicate-sulphide rocks that comprise the orebodies and companion lithologies. Specifically, this contribution aims to clarify and expand on the work of Andrews (1922), Gustafson (1939), Gustafson et al (1950), Hodgson (1967, 1974, 1975), Maiden (1972, 1975), Boots (1972), Lawrence (1967, 1973) and Webster (1993, 1994a) by further documenting the structural evolution of the deposit, using the evidence that is preserved within the mineralised rocks, their companion lithologies and the adjoining wall rocks.

The chapter structure of this thesis reflects the above-listed aims. The first core chapter (Chapter 4) describes and documents the stratigraphic features of the BHI mineralised system and its host sequence. This part seeks to build on the work of Jaquet (1894); Andrews (1922); Gustafson (1939); King & O'Driscoll (1953); Carruthers and Pratten (1961); Johnson and Klingner (1976); Laing et al., (1978) and Haydon and McConachy (1987). The second two core chapters (Chapter 5 and Chapter 6) focus on the structural evolution of the mineralised system and its later geological history. Chapter 7 presents a summary of the structural history of the deposit and discusses the environment of formation of the orebodies.

### **1.3.2. Geological Synthesis of the Broken Hill Deposit.**

A significant component of this research comprised a comprehensive reinterpretation of the geology of the orebodies and their immediate wall rocks, based on factual mapping information. To the author's knowledge, no workers since the Central Geological Survey of the 1930's (Gustafson, 1939; Gustafson et al., 1950) have attempted a complete synthesis of the geology and structure of the Broken Hill orebodies and their work represents the key data in the current study. While one worker could never hope to completely synthesise the details of the geology of this immense deposit, the current study has made an attempt at a comprehensive overview, which will provide a firm context for future researchers. During this reassessment, an emphasis was placed on the following;

1. The definition of fold, shear and fault structures that are present within the ore and near-ore environment. This aspect of the project has been necessary to provide a firm basis for structural modelling. It is also important because it represents the best way of avoiding an uncritical application of information from small and isolated areas of field observation to the entirety of this giant deposit,
2. Compilation of interpretative geological maps of the main mine openings in all major mines of the Line of Lode. While data has been available for over 70 years, no detailed interpretative geological maps of the underground levels have previously been compiled (with the exception of the plan of the 36 Level, North Mine, published in Leyh and Hinde (1990)
3. A mapping-based assessment of the geology and structure of the 'Zinc Lodes' and their host rocks. Workers such as Matthias (1973) and Billington (1979) utilised diamond drill core to complete petrology-based studies of aspects of the 'Zinc Lodes' however no comprehensive reinterpretation of the geology of these important mineralised zones has been undertaken. This study places the 'Zinc Lodes' into their structural and stratigraphic context within the entire deposit for the first time.
4. During the course of the research it has also been found necessary to define and map where possible, the distribution and textural variations of gangue species within the orebodies. This information is critical to the determination of the internal stratification and structure of the orebodies, their structural history and the effects of metamorphism. This aspect of the deposit is also one that has been neglected by previous workers. Previous studies have focussed on the identification of mineral species from particular localities however the geological environments, habits and textural variations in mineral species have been poorly reported.
5. The definition of the internal structure and geology of 1 Lens Upper and Lower and A Lode Upper and Lower which have only been discussed in passing by previous workers.

6. The definition of the internal structure and geology of 3 Lens and 2 Lens and their relationship to the structure of the surrounding rocks and the structure of the mining field.

This thesis does not discuss the Pasminco Mine below the 21 Level Southern Cross in detail. Recent research by A. Morley (MSc thesis, in prep) and ongoing exploration and interpretation by mine geologists will more completely deal with this important region of the mine.

#### **1.4. SUB-REGIONS OF THE BROKEN HILL MINING FIELD.**

For convenience, the names of former mines and mining leases will be used throughout this thesis as a means of referring to geographic regions within the mining field (Figure 1.1b). Brief histories of former mines are presented in Appendix 2. The Line of Lode is also divided into four sub-regions that approximate structural domains within the deposit (Figure 1.1b). Sub regions are defined as having similar structure, orebody geometry and lithological associations. This section provides a definition of the sub-regions used.

##### **1.4.1. The Southwestern Region.**

The southwestern region incorporates all of the current Pasminco Broken Hill Mine (the location of the former Zinc Corporation Ltd and New Broken Hill Consolidated Limited Mine). Also included are the leases of the former South Broken Hill Ltd mine (ML's 6, 7 and 8) and the sites of the former Central and Block 10 Mines (ML's 9 and 10) and which lie within the current CML 7.

The common characteristics of the deposit in the southwestern region of the mining field continue into ML 11 of the former BHP Mine (now a part of CML 7) and this area is therefore also included (Figure 1.1b).

##### **1.4.2. The Central Region.**

The central region is defined as that part lying within Consolidated Mining Lease number 7 (CML 7) and comprising the former mining leases (ML's) 12 to 15. It



incorporates the majority of the leases of the former Broken Hill Proprietary Company Limited Mine (ML's 12 & 13) (Figure 1.1b).

#### **1.4.3. The British-Junction Region.**

The British-Junction region straddles the Menindee Rd area and incorporates the leases of the Broken Hill Proprietary Block 14 Company Limited Mine (ML 14), the leases of the British Mine (ML 15 and 16) and ML39 of the former Junction Mine (Figure 1.1b).

#### **1.4.4. The Northeastern Region**

The northeastern region incorporates all of the former North Broken Hill Limited mine (Pasminco Northern Operation) and the Junction (part) and Junction North Mines. Also included within this region are the Fitzpatrick orebody at depth in the North Mine (Figure 1.1b).

**Figure 1.2. Characteristics of Broken Hill Type Pb-Zn-Ag Deposits (modified after Walters, 1996b).**

TARGET	REGIONAL GEOLOGICAL CRITERIA	LOCAL GEOLOGICAL CRITERIA
Too few economic examples to develop a robust average, examples used range from 30 to >250 Mt	Restricted age range in Palaeo-Mesoproterozoic mobile belts with long thermal histories. Hosted in amphibolite-granulite facies metamorphic terranes.	Thin exhalite units (e.g. quartz-gahnites) define lateral markers & prospective packages,
Large single deposits dominating a district are the norm.		Multiple 'exhalite' horizons are common.
Economic grades approx 10-20% Pb+Zn. Strong Pb-Zn zonation trends	Rift related tectonic setting, with a transition from quartzo-feldspathic dominant lower stratigraphy to psammopelitic & pelitic sequences in upper stratigraphy. BHT mineralisation concentrated at transition from lower to upper sequences.	Graphite & pyrite are not common in near ore environments.
High Pb,Zn & very high Ag (>100ppm) are characteristic.		Other styles of mineralisation occur in BHT districts, in particular ironstone associated Cu-Au in lower stratigraphies.
High Cd, Sb, Mn & Fe, with localised elevated As, Cu, W, Bi & Au	Oxidised clastic metasediments are most probable host lithologies.	Concentration of amphibolites & possible acid volcanics in near ore & footwall sequences.
MINERALISATION FEATURES	ALTERATION	DEPOSIT GEOCHEMICAL CRITERIA
Mineralisation hosted by diverse range of skarn-like Ca-Mn-Fe-P-F rich assemblages. Galena- sphalerite dominate with subordinate pyrrhotite & minor pyrite.	No obvious focussed footwall feeder zones with intense alteration.	High levels of Mn-Ca-Fe-P-F in gangue, high As, Bi, Sb & Ag in minor sulphides phases.
Variable magnetite.	More abundant sillimanite & disseminated garnet form large-scale stratabound alteration envelopes in host quartzofeldspathic sequences	Extreme zonation between siliceous Zn-rich & more Mn-Ca-Fe 'calc-silicate' Pb-Ag rich end members.
Coarse grained recrystallised & annealed textures, with complex ductile breccias	High levels of K-feldspar in alteration halos, are associated with 'lode pegmatite' sweats, often with pale green Pb-bearing amazonite.	High F & Cl associated with fluorite, apatite & amphiboles.
Stacking of low aspect ore lenses is common.	Fe-Mn garnet 'quartzites' & 'sandstones' form immediate envelope to ore system.	Widespread Pb-Zn-Mn anomalism in thin regional marker horizons.
Strong Pb-Zn zonations, with rapid variations.		Elevated base-metals in non-sulphide phases e.g. gahnite, feldspar and magnetite.
High Mn-Ca-Fe expressed as garnets, pyroxenes & pyroxenoids, e.g. bustamite, pyroxmangite, rhodonite & spessartine.		High Ag/Pb ratios with argentiferous galena & freibergite the most common primary Ag-bearing phases.
Structural upgrading & complex retrograde metasomatism are characteristic features.		Strong fractionation of REE's, in particular Eu.
FLUID CHEMISTRY & SOURCE	GEOPHYSICAL CRITERIA	SURFICIAL GEOCHEMICAL CRITERIA
Fluid chemistry of BHT's difficult to define due to the metamorphosed nature.	Variable magnetite association; only minor magnetite in the BH Main Lode but is an important component of the Pinnacles deposit near BH & at Cannington & in the Aggeneys group of deposits. Produces a direct magnetic target	All listed examples, except Cannington, were discovered by prospecting of prominent outcrops.
Low Cu levels suggest temperatures below 250°C. Lack of Mg-rich alteration assemblages.		Ca-Fe-Mn rich zones may form spectacular gossans, with Pb-rich Mn oxides.
Nature of host sequences & general lack of pyrite indicates probable oxidised ore fluid with $SO_4 > H_2S$ .	Pyrrhotite is the dominant Fe-sulphide, but tends to occur in discrete zones responsible for variable EM responses.	Soil & stream sediment anomalies associated with exposed examples.
Most BHT deposits characterised by extensive retrograde metasomatism which may involve externally derived fluid overprints.	Graphite not a common association with ore.	Thin lateral markers easily overlooked in wide spaced surveys.
	Garnet, Fe-rich pyroxene, pyroxenoid. & amphibole rich, with galena-rich mineralisation = strong gravity contrasts.	Zn-spinel gahnite is a characteristic mineral in regional markers, but is a resistant phase not easily digested in routine analysis.

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## CHAPTER 2: PREVIOUS WORK

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### 2.1. INTRODUCTION.

Charles Sturt made geological observations in the Broken Hill (BH) region in the 1840's, however systematic geological observations and scientific investigations only began shortly after the discovery of the orebodies in 1883. Charles Rasps "heavy black samples", collected on the hill in 1883, were assayed but contained only minor silver and lead (Blainey, 1968). One hundred and nineteen years of mining and exploration at BH has seen a corresponding length of geological research, so the BH scientific literature is immense and a summary is necessarily lengthy. The purpose of this chapter is to provide a summary of the earlier relevant research, which will then form a background to the current project.

The research interest in the BH deposit has stemmed from its mineralogical diversity, richness and size and the desire by mining companies to mine and treat its ores more economically and safely. More recently, research has been focussed on the discovery of further in-mine or near-mine ore resources and/or to aid the discovery of similar deposits in other regions. A considerable amount of mineralogical research has been conducted on the diverse and often spectacularly formed mineral species that have been discovered in the primary sulphide, and secondary oxidised zones of the deposit.

### 2.2. PREVIOUS GEOLOGICAL INVESTIGATIONS.

Several phases of geological investigation have taken place at BH. They can be categorised as shown in Figure 2.1.

#### 2.2.1. Early Investigations (1890's to early 1900's).

The structure of the mineralised system, and its relationship to ore genesis was one of the earliest concerns of researchers. Pittman (1892) recognised the generally antiformal ("saddle") shape of the orebody (3 Lens) in the central region of the field; noted its conformity with the surrounding metasediments and drew analogies with Bendigo

style saddle reefs (see Chapter 6). He suggested that the limbs could be expected to thin out at depth and orebody repeats would be found at depth if the Bendigo analogy were correct. He suggested the lode had formed from the infilling of cavities developed during folding, with some associated wall rock alteration.

**Figure 2.1.** *Phases of geoscientific investigation at Broken Hill. The most recent phase, from the early 1990's to present, is mainly represented by the Broken Hill Exploration Initiative (BHEI) with some independent studies.*

PHASE OF INVESTIGATION	MAIN RESEARCHERS	RESEARCH ORGANISATION	FOCUS
1890's	Pittman (1892), Jaquet (1894) Marsh (1890, 1893)	Government (GSNSW) Mineralogists	Mineralogical research, some structure, early genesis theories.
1890's-early 1900's	Metallurgists Scientific Society of Broken Hill (1910)	Mining companies Consortium of mine professionals	Metallurgical research & development leading to sulphide flotation First comprehensive description of deposit
1920's	Andrews (1922) Stillwell (mineralogical)	Government (GSNSW)	Describing the orebody environment & regional geology
Late 1920's – early 1930's	Kenny 1922, 1928, 1929 H. C Burrell	Government (GSNSW) Company geologist	Early structural geology investigations of the mining field. Early geological mapping at the Zinc Corporation
Late 1930's	Central Geological Survey (Gustafson, 1939)	Mining companies Establishment of geology departments on some mines	Compilation of the geology of the field for exploration - the most significant compilation of the geology of the field ever undertaken
1940's	Geological Department North Mine	North Broken Hill	Establishment of systematic geology recording systems and proving of economic value of geology in mining & exploration
Late 1940's	Zinc Corporation: King & Thomson, O'Driscoll Stillwell & Edwards	Mining companies CSIRO Mining companies (ZC & North)	Mine-based categorisation of geology Mineralogical / petrological work. Regional geological mapping
Late 40's early 1960's	Henderson (1953) H F King & B Thomson. Fifth Empire Mining & Metallurgical Congress-Australia and New Zealand Publication of the <i>Geology of Australian Ore Deposits</i> .	Companies	Geological mapping & exploration of the Northern Leases. Late 1940's to mid 1960's (ZC Mines, orebody geometry and understanding of the ore environment - development of syngenetic concepts & definition of the "Zinc Lodes"), Syngenetic model
Late 1950's	Zinc Corporation F L Stillwell & A B Edwards	Company researchers CSIRO	Counter-arguments to the syngenetic model – major debate
1960's-70's	Hobbs Laing Laing et al	Company sponsored university researchers, particularly UNSW, & Adelaide University Government (GSNSW)	<i>Period of major research effort.</i> Regional mapping/exploration Late 1960's to 1980's (with university, government and company based / funded research programmes, structural geology)
1980's - 1990's		Company researchers, chiefly Pasmunco GSNSW, AGSO & PIRSA	<ul style="list-style-type: none"> <li>Regional geology</li> <li>Orebody structural environment</li> <li>Deep crustal structure</li> <li>Orebody genesis</li> </ul>

Marsh (1893) produced the first published surface geological map of the mining field, followed closely by Jaquet (1894), who undertook the first detailed study of the geology of the field and produced the earliest geological map of the district. Jaquet (1894) considered the rocks hosting the lode to be "pre-Devonian", suggesting upper or lower Silurian, or possibly older. He also noted the strike of the lode to be parallel to the surrounding country. He classified the orebody as a "saddle type" but noted the departure from the symmetrical form and suggested that the garnet in the lode was probably derived from the wall rocks. He suggested that the lode originated as a mechanically produced fissure that had undergone enlargement by the actions of mineralising fluids.

Smith (1897) showed the rare silver minerals present in the lode to be of secondary origin and suggested their formation was due to "descending waters". Smith also recognised gahnite at BH for the first time. Jamieson and Howell (1893) produced the only published maps of the oxidised zone, which, along with the long section of the deposit reproduced in Jaquet (1894), and the more general plans reproduced in annual reports of the Broken Hill Proprietary company Ltd (e.g. BHP Company Ltd., 1895), form the main record of the geological features of the oxidised zone of the field (see Chapter 6)

Beck (1900) agreed with Jaquet (1894) that the BH orebody was of a "saddle type", but one that differed from the norm because it was a "replacement body" that had metasomatic alteration and replacement along the lode borders (i.e. they were not just simple cavity fillings). He classified the deposit as being of a "Broken Hill type" of "saddle" and compared it to the Silverberg at Bodermain deposits (Germany), where the lode is located on a crushed and faulted zone. He also recognised rhodonite. Gregory (1904) considered the BH orebody to be an atypical saddle reef because it was related to a fault plane. He did not believe that an open cavity could have existed in which a 'saddle' reef could have developed. He also suggested that the wall rocks were not sediments but altered granites of "Archaean" age.

A considerable controversy raged over the genesis of the BH orebodies, even in 1908. The government geologists, Pittman and Jaquetm, favoured the segregated 'Bendigo' type saddle reef theory and were supported by E. J. Horwood (manager of the Proprietary Mine) and G. Hebbard (manager of the Central Mine). Professor Gregory,

J Warren and "many others" opposed the theory (Stokes, 1908). This controversy may be what caused the comment by the Scientific Society of Broken Hill (1910) about "theory building", in the introduction to their paper two years later (see below).

Andrews (1908) noted that the hanging wall (northern side of the deposit) orebodies are all directly connected to tabular footwall (southern side of deposit) orebodies. He suggested that the footwall lode was in fact a zone of dislocation along which mineralising fluids had ascended and replaced puckerings produced by crumpling of the hanging wall country against the footwall during deformation. He emphasised the special methods of shearing and fracture, which developed the line of weakness along which the ore bearing solutions rose. He cited the major gangue minerals as being evidence for intense alteration of country rock to lode.

The Scientific Society of Broken Hill (1910) undertook to record all of the geological information that was available at the time. They stated, "Theory building was to be a secondary consideration", partly because they felt it was better left to specialists and partly because they felt that BH geology, like most other mining geology, had "suffered from too much theory". The Scientific Society of Broken Hill (1910) recorded most of the general geological features of the deposit that are recognised today, particularly its doubly plunging nature, complex folded geometry and intrusion by narrow dolerite dykes. They decided that the western margins of the saddle-like orebodies pinched out along bedding planes (as Bendigo gold reef saddles do), but recorded that the majority of staff on the mines considered the western termination to be a synclinal fold (this is true in many instances). They concluded that faulting had played a major part in the formation of the orebodies and that folding, while important, was of secondary importance. Consequently, they downgraded the saddle theory.

Mawson (1912) mapped and surveyed the Barrier Ranges region with an emphasis on the age relationships and petrology of the rocks of the region. He named the belt of metamorphic rock in which BH occurs the "Willyama Complex". He also undertook some work on the mining field, where he noted the change in symmetry of the saddle shape with depth and suggested that there would probably be more than one enlargement. He also noted the importance of the influence of folding of the schists and gneisses on the nature of the orebody, suggesting that this was in accord with the means by which saddle reefs form. He quotes an example from Tombstone, Arizona,

where the largest orebodies are at the intersection of veins and anticlines. Mawson (1912) observed a fault structure containing a dyke-like body of ore extending down from the main ore bulge and considered it to be evidence of the partial replacement of the structure by mineralisation. He noted the association of such faults with the widest parts of the structurally complex orebodies and concluded that the formation of the faults had preceded the formation of the orebodies. The faults had acted as conduits for a watery mineralising solution which was derived from a differentiating magma, now represented by granite gneisses. According to him, the gangue mineralogy (especially fluorite and apatite) was evidence for a granitic origin. Mawson (1912) associated the common pegmatites with the ore forming process, calling them 'ore bringers' and suggested that they were genetically related to the ore forming process. He dated the mineralisation as "Palaeozoic or even Precambrian".

Moore (1916) suggested that the presence of sulphide, fluorite and quartz inclusions within garnet (as well as being found filling spaces between garnets and overgrowing them), showed that pulses of metasomatic replacement had occurred. He suggested that the saddle structure of the orebody had been produced by the selective replacement of beds within the saddle, giving it the appearance of a conformable origin. This was the first time that the selective replacement of sedimentary layers had been put forward as a mechanism for the formation of the orebody rather than the cavity infilling models of earlier workers. He suggested that the tabular ore zones associated with the saddles had acted as channels for ore fluids. Moore (1916) interpreted masses of mineralisation that were detached from these tabular zones to have formed from the selective replacement of beds by ore fluids working their way along fissures and bedding planes.

Eventually the details of orebody geometry proved to be very complex and it was realised that an understanding of this complexity, prior to mining, would lead to significant savings in development and mine planning costs. So in the 1930's, mine geology departments were formed to define the orebodies by drilling and mapping, before they were developed, so that accurate planning for mining layout, production scheduling, ore reserves and stope development can be undertaken (e.g. Garretty, 1943). They also explored the orebodies at depth, and their successes or failures allowed the mining companies to plan their strategic development more accurately.

### 2.2.2. 1920's and 1930's.

A major focus of the research effort in the third phase of scientific interest at BH focussed on geological investigations to determine the longer-term potential of the field. Geological work, mainly driven by government, and later company co-operative efforts, took a holistic approach to understanding the geology of the mining field and surrounding districts and sought to identify the ore potential of the existing orebodies at depth. This phase of investigation led to a huge capital investment in the field by Zinc Corporation and North Broken Hill Limited and led to the departure from the field of BHP Ltd. Smaller companies with minimal ore potential were slowly consolidated with the larger mines of the field in the early 1940's.

Andrews (1922) undertook a comprehensive regional and deposit scale investigation of the BH district, presenting the earliest underground mapping from the South and British Mines. He produced the first detailed regional geological map of the district (only superseded in the 1950's) and developed a rock-type classification that was still in use in 1953 (King and Thomson, 1953). He aimed to place on record any information which might be of use to future prospecting and in so doing produced a detailed treatise on the geology of BH which contained reports on regional petrology (Browne, 1922), rocks in the immediate vicinity of the orebody (Stillwell, 1922) and descriptions of the individual mines then operating (Kenny, 1922). The surface mapping undertaken along the outcrop area of the mining field by Andrews (1922), has not been surpassed in quality, except perhaps by that of the Central Geological Survey (Gustafson, 1939). In many cases it is the only record of outcrops that have since been destroyed.

Andrews (1922) discussed the structure and genesis of the orebodies at length. He noted that 'zones of crush' (shear zones) developed by a tendency of fold limbs to glide along one another and recognised that 'rock flowage' rather than 'ordinary rupture characterised the method of movement or gliding'. He believed that these 'crush zones' provided channels of circulation for the mineralising fluids given off at depth by igneous material and thought that the mineralising fluids ascended these zones along a pressure gradient. Where the pressure decreased there was a tendency to form sills or lenses of ore in the footwall crush. He stated that these fluids had a tendency to leave



no sign of their passage. He also recognised the silicification of the wall rocks adjacent to the lode.

Andrews (1922) recognised a relationship between the BH type mineralisation and the magnetite rocks located near it. He stated that magnetite lodes were developed within these zones at depth but explained these bodies by differential replacement of sediments. He noted the entire spectrum of quartz magnetite (banded iron formation, BIF) rock-types, concluding that they are probably replaced sediments formed in a similar manner to the orebody. He decided that the lode area had been more strongly metamorphosed due to heat derived from underlying intrusives, thus changing the sediments to gneisses. Following the metamorphism, zones of crush developed along which fluids migrated. Andrews (1922) identified the major macroscopic folds within the area of the Mining field (The Hangingwall "Basin" and Broken Hill "Basin", now known as the "Broken Hill Synform" and the Hangingwall Synform; see Chapter 5).

Stillwell (1926) undertook the first comprehensive microscopic investigation of BH ores and later investigated the mineralogical associations of gold (Stillwell, 1940) and cobalt (Stillwell and Edwards, 1939; 1944).

Kenny (1928; 1929; 1932) completed a number of reports into the structure of the orebodies. He recognised the high-grade shears that deformed the orebodies, but interpreted them to be ore fluid conduits, contemporaneous with mineralisation, rather than deforming structures.

Gustafson (1939) and Gustafson et al., (1950) undertook a comprehensive survey of the geology of the mines and their immediate environs, pioneering many of the procedures that were later adopted by mine geology departments in BH. These workers formed the Central Geological Survey (CGS), a group assembled by the major mines of the field to document the geological features of the deposit in detail. The ultimate aim of this work (which took place in 1936-39) was to assess the possibility of major repetitions of the orebodies and to aid the staff of the mines to better understand the orebodies. A third aim was to provide a source of information for areas that would be inaccessible *"when Broken Hill again feels the need of a comprehensive geological examination"*.

The work of Gustafson (1939) and his co-workers probably ranks as one of the great works of pre World War 2 geology. They recognised the correlation between particular gangue-mineral assemblages and stratigraphic position and identified all the features that distinguish 2 Lens and 3 Lens (and named them). Gustafson (1939) recognised the layered nature of the ore lenses and expanded the "favourable bed" replacement model, citing the intersection of these beds with the Belt of Attenuation as being the most important control on the replacement process. The variation in gangue type within the various lodes was interpreted to reflect variations in the original, replaced sediments. Gustafson and his co-workers defined many details of the mine stratigraphy and recognised that correlation was possible throughout the mining field. Gustafson (1939) outlined the important structural features of the immediate mine area, including: the "Western Antiform", "Eastern Synform", Belt of Attenuation and most of the major shear zones. They recognised the relationship between the Main shear and the Belt of Attenuation and classified the shear zones into two types based on their orientation (see Chapter 5).

H. C Burrell was employed as a geologist at the Zinc Corporation in the early 1930's and began to produce some of the earliest methodical geological mapping of the mine levels of the Pasminco Mine (Zinc Corporation Ltd., unpublished data, 1932). He became a member of the Central Geological Survey (CGS) with K. J. Gustafson and M. D. Garretty in 1936. Following the completion of the work of the CGS he undertook a laboratory and statistical analysis of gangue mineral distributions within the orebodies (Burrell, 1942). His aim was to determine if the mineralogical differences between the major ore lenses that had been recognised by the CGS were truly diagnostic of each orebody. His results confirmed the distinct nature of 2 Lens, 3 Lens and the "siliceous" and "rhodonitic zinc lodes". He provided a mineralogical method of recognising the ore types rather than the metal ratio system that had been used previously. Burrell (1942) suggested that the manganese silicates and calcite in the orebodies were metamorphic in origin and only recrystallised by the ore forming solutions (i.e. they pre-dated the mineralisation). This conclusion pre-empted the stratiform, pre-metamorphic model of King and O'Driscoll (1953) by some 10 years. His co-workers (M. D. Garretty and H. K. Gustafson) believed the manganese silicates to be hydrothermal in origin but deposited in a paragenetic sequence in which sulphides were deposited later (Gustafson et al., 1950).

The climax of this period was the presentation of the results of the CGS in Gustafson (1939) and the constitution of the North Broken Hill Ltd Geological Department in 1939 (Parkin, 1940; Garretty, 1940)

Subsequent interest in the structure of the BH deposit has originated from two main sources. The first is the largely mining company and government funded research aimed at understanding the geological controls, and characteristics of the mineralised system, so that extensions to known orebodies might be discovered, or so that apparently sub-economic zones may be brought into ore reserves by increased geological understanding. The increased geological understanding of the BH mining field may also lead to the recognition of similar deposits in other terranes, or parts of the BH district. The second driving force behind post-war geological research has come from the theoretical geoscientific desire to understand the details of the geology of the mineralised system (i.e. the origin of the shape, the mineral constitution and the near-ore geological environment), and thereby understand the genesis of the deposit. This aspect has been largely university funded).

### 2.2.3. 1940's to 1960's.

The war years hampered geological investigations at BH and prevented the publication of the results of the CGS until 1950 (Gustafson et al., 1950; 1952). However, some geologists remained active, most notably M. D Garretty at the North Mine, where the procedures of geological data collection and storage (mine geological plan systems) were put in place and which were to remain essentially the same for the next 50 years.

Since the 1940's, the majority of research has also focussed on the understanding of the structural and stratigraphic environment of the orebodies so that new orebodies may be found in the BH region, in analogous terrains elsewhere and to guide the more economic targeting of deep exploration programmes in the mines area.

A petrological investigation of ore specimens from the BH orebodies was completed by Ramdohr, (1951). From this work he concluded that the deposit had been metamorphosed and that there was probably no paragenetic sequence of mineral deposition. He cited deformed grains of molybdenite and graphite occurring within undeformed sulphide or gangue crystals as evidence. He observed that any sulphide

or gangue mineral could occur as rounded inclusions in any other phase, suggesting that such textures showed the all mineral phases had co-crystallised.

King and O'Driscoll (1953) reported the results of extensive mapping within the Pasmenco Mine (and the deeper levels of the South Mine) that had been accumulated from 1946-53. They applied this information to a reinterpretation of the geology of the entire mining field, with a heavy bias toward the work of Gustafson et al. (1950). King and O'Driscoll (1953) concluded that the BH orebodies had been deposited as "a simple stratigraphically disposed body conformable with the enclosing sediments". With knowledge of the petrological work of Ramdohr, (1951), who showed that the ore had been metamorphosed after formation, they went on to state; "Its constituents suffered recrystallisation, concentration and migration under the influence of severe structural deformation which was probably concurrent with the successive waves of migmatism". These deceptively simple statements at the end of their paper sparked off one of the greatest geological controversies that Australia has seen. Most of the university research effort of the 1960's to 1980's can be traced to the 1953 paper by King and O'Driscoll, and the debate that it sparked.

King and Thomson (1953) reported the results of a regional mapping campaign undertaken by the Zinc Corporation from 1946-51 and produced the first regional geological map since that of Andrews (1922). Thomson (1952, 1955, 1959) is credited with the recognition of the stratigraphic approach to the regional interpretation of the Willyama Complex and recognised and named the Broken Hill Group as the host to base metal mineralisation (in Willis et al., 1983).

Stillwell and Edwards (1956) and Stillwell (1959) argued consistently against the stratiform-metamorphosed model proposed by King and O'Driscoll (1953). Their major line of argument centred on the observation that late intrusive dolerite dykes that cross cut the orebodies in several places in the BHP and North mines were altered ("uralitised"). They argued that these dykes preceded the replacement process, which had formed the orebodies, and although not replaced themselves, the mineralising process had extensively altered them. Stillwell (1959) was also a champion of a set paragenetic sequence of minerals existing in the ore and their hydrothermal origin, interpretations that Ramdohr, (1951) had discounted. Stillwell's main flaw was that he

interpreted the genesis of the deposit by ore textural evidence alone; he ignored the large amount of field evidence for the syngenetic origin of the lodes.

Condon (1959) identified sedimentary structures within the metasediments of the Willyama Block after being asked to examine these rocks for such features by Haddon King (Chief Geologist of the mine). The structures he identified were claimed to be tectonic in origin after re-examination of the localities (Edwards, 1959). Condon (1959) observed structures that he identified as large-scale cross bedding within the garnet quartzite above 2L on the 20 Level of the Pasminco Mine. While it is likely that this region of the orebody lies within the Western zone of transposition and folding (Webster, 1993) and therefore, these structures are probably tectonic, the writer has collected one specimen of a very cross-bed-like structure from garnet quartzite above A Lode, which fits Condon's description very closely. So his observation cannot be completely discounted without examining his original locality (which is inaccessible). Condon (1959) went on to describe several "sedimentary" structures within the ore itself and concluded that the mineralisation was sedimentary in origin. The places where he identified these structures (cross-laminations and possible sedimentary slumping) are some of the most deformed areas of 2L (southern side of the Pasminco Mine) and so must be discounted. However this does not mean that his conclusions were necessarily incorrect. The origin of the banding within the orebody is a very early feature (Webster, 1993; 1994a) and the process that formed it is not known. Condon may ultimately have been proven right in essence, if perhaps not in detail by Laing (1977a and 1977b) and Laing et al, (1978) who confirmed the presence of graded bedding in the metasediments of the Broken Hill Group. The replies by Edwards (1959) and Williams (1959), which follow Condon's paper of 1959, make interesting reading from the point of view of how vehemently any suggestion of a syngenetic origin for the BH orebody was attacked at the time.

Lewis et al., (1965) produced an excellent paper in which they reviewed all the evidence that had been cited in support of the various genetic theories then under discussion. They believed that the evidence for all models was ambiguous when closely scrutinised and concluded that the issue was unresolved. However they did state their preference for the epigenetic model and discussed the various pieces of evidence that had led them to this conclusion. In their opinion, two pieces of evidence stood out as making the syngenetic origin very unlikely. These were:

- (1) The close association of folding to ore distribution. They believed that such a distribution could only be the result of epigenetic processes, as it would require too much redistribution of metals and gangue to produce this geometry. They could not visualise a process that could produce such large-scale redistribution into folds, and
- (2) The presence of unstressed sulphides within faults (such as the British Shear) which were texturally the same as other parts of the orebody.

The reasoning by which Lewis et al., (1965) objected to a syngenetic origin for the lode is flawed because of their lack of knowledge about the processes of sulphide mobilisation and the ore textures that it can produce. This is understandable however as little if any work had been done on the textures of deformed and mobilised BH ores at this time. They suggested that existing petrological studies gave conflicting results and proposed that post-emplacement recrystallisation may have modified the mineral relationships.

Several papers dealing with the general geology and mining operations of individual mines have been written since the 1950's, mainly as part of the Geology of Australian Ore Deposit volumes. Major papers include Henderson (1953), Black (1953), O'Driscoll (1953), Pratten (1965), Hawkins (1968), Mackenzie (1968), Mackenzie and Davies (1990), Van der Heyden and Edgecombe (1990), Widdop (1983) and Leyh and Hinde (1990).

Since the mid 1950's, important interpretative papers on the BH deposit have been produced by company personnel (largely from the Zinc Corporation). These publications focussed on two aspects of BH geology,

- (1) Revisions of the structural and stratigraphic environment of the orebodies, and
- (2) Interpretations of the regional setting of the deposit. They have tended to be of a revisionist style, incorporating new information and concepts as they have become available. Important papers include Carruthers and Pratten (1961), Carruthers (1965) and Johnson and Klingner (1976).

Since the 1950's, academic interest in the BH deposit has largely focussed on the development of genetic models and, according to Barnes (1988), took two separate directions;

- (1) Sedimentary-biosedimentary concepts and

## (2) Exhalative hot springs genesis.

The latter view has tended to hold the most sway until the recent work of Haydon and McConachy (1987), Wright (1985) and Wright et al. (1987). This work is described more fully below.

Stanton and Russell (1959) and Stanton and Richards (1961) suggested that the deposit may have been formed by the volcanic exhalative processes which were then just being understood for Australian and (earlier), Japanese volcanic hosted massive sulphide (VHMS) deposits. This work resulted in the wide acceptance of a vulcanogenic model for the origin of BH. An alternative view suggested that the deposit might have been derived from the large volume of the Willyama Supergroup rocks by "metamorphic transformation" (Rattigan, 1960). Additional support for a volcanic exhalative origin for the BH orebodies has come from extensive investigations into the quartz-magnetite rocks (BIF) and their inferred relationship to mineralisation (e.g. Richards, 1963; Stanton 1972, 1976a, 1976b, 1976c, 1976d).

Regardless of whether the orebodies were deposited from volcanically derived fluids, sedimentary exhalative fluids, or some other mechanism, they are regarded by many workers to have been deposited as chemical sediments (see Chapters 4 and 7).

### 2.2.4. Late 1960's to 1980's.

The late 1960's to the early 1980's was a period of intense structural geological investigation in the Broken Hill Domain, and in the mining field itself (e.g. Hobbs, 1966; Hobbs and Vernon, 1968; O'Driscoll, 1968; Laing et al., 1978; Marjoribanks et al., 1980). Much of the investigation was to determine whether the orebodies were deformed along with their surrounding host rocks. At the same time company geologists and consultants were further investigating the stratigraphic setting and sedimentary environment of the orebodies (e.g. Wright, 1985, published as Wright et al., 1987 and 1993; Haydon and McConachy, 1987) to determine whether there were recognisable stratigraphic environments and indicators to the presence of economic mineralisation. In the late 1970's the Geological Survey of NSW commenced a major regional mapping programme in the Broken Hill Domain that has only recently been completed (e.g. Stevens et al., 1983; Willis et al., 1983)

O'Driscoll (1968) carried out a detailed investigation of the tectonic setting of the BH orebodies, in relation to crustal scale lineaments. He also discussed the structure of the mineralised system at a deposit scale, interpreting it to have been deformed by shear related drag folds. One of his most interesting interpretations of the structure of the mining field was the conclusion that the major plunge reversal in the centre of the field was caused by an antiformal structure with an axis trending some 20 degrees to the strike of the orebody. This finding has been supported by the current study (see Chapter 5).

Hobbs (1966, 1968) analysed the structure of the North Mine area and concluded that there were four recognisable groups of structures (Figure 2.2). He inferred that 2L and 3L at the North Mine were probably not originally conformable to the surrounding wall rocks and that the folds at the northeastern end of the deposit were probably not related to those at the southwestern end. He favoured a structural emplacement of the orebody. Ransom (1969) undertook a microscopic and macroscopic structural study of the southern part of the mines area and identified four groups of fold structures (Figure 2.2). The first two developed at granulite grade and the second two developed at almandine-amphibolite metamorphic grades. His classification scheme followed that of Hobbs (1966).

GROUP	FOLD STYLE	LOCATION	ASSOCIATED STRUCTURAL FABRIC
Group 1 folds	isoclinal	restricted to lithological layering	axial plane foliation & sillimanite parallel to axes
Group 2 folds	more open than Group 1 folds	co-axial with Group 1 folds	defined by a high-grade schistosity and/or lithological layering
Group 3 folds		defined by high grade layering within retrograde schist zones	retrograde, axial plane schistosity.
Group 4 folds	minor crenulations		In retrograde schistosity

*Figure 2.2. Fold generations identified by Hobbs (1966) in the North Mine area, Broken Hill and also used by Ransom (1969).*

Ransom (1969) concluded that there was insufficient field and laboratory evidence to say whether the orebody had undergone the same structural and metamorphic history as the wall rocks and doubted that the orebody was conformable with the



metasediments. He suggested that the mine area had been transposed on a regional scale and that the stratigraphy was therefore not a true stratigraphy as such and described the folds developed within the orebody as "chaotic in style and geometry".

Ransom (1969) carried out a microscopic investigation of the internal structure of the retrograde shear zones of the BH area and Vernon and Ransom (1971) described the mineralogy of the retrograde shear zones, concluding that they had formed at lower amphibolite grade.

Further investigations into aspects of the structure of the BH area were undertaken by Marjoribanks and Laing, (1975) and Rutland and Etheridge, (1975). Laing, (1977a) undertook a detailed structural investigation of an area to the immediate north of the North Mine. He applied this work directly to the southern part of the orebody during a three-month contract for the Zinc Corporation (Laing 1977b). Laing (1977b) and Laing et al (1978) reinstated the Broken Hill Antiform, (previously suggested by Gustafson 1939 and dismissed by Carruthers, 1965, and Carruthers and Pratten 1961). The most significant result of Laing et al's., (1978) reassessment of the mines was the interpretation that the mine stratigraphy is structurally repeated

Laing et al (1977a) and Laing et al., (1978) concluded that the position of the 'Broken Hill Antiform' was occupied by a "slide", represented by a series of dislocations parallel to bedding. He could not firmly identify an antiformal closure in the mine area and no one has been able to since (e.g. Rothery, 2001). However, their model is still the generally accepted structural model for the region, published in the paper by Laing et al., (1978). The position of the 'Broken Hill Antiform' remains one of the greatest problems with this structural model and is discussed in Chapter 4 and 5.

Laing et al., (1978) produced the structural interpretation that is still the generally accepted model for the region. They identified graded bedding within the metasediments, from which accurate facing information could be obtained, and from which they concluded that the mine area had been overturned. They interpreted the structure of the mining field in terms of three roughly coaxial deformation episodes. D1 and D2 were associated with high-grade metamorphism and D3 was associated with retrograde metamorphism and the initiation of retrograde shearing. D1 was associated with overturning of the mine area and the development of a strong foliation

(S1) parallel to bedding. D2 was associated with a strong axial planar foliation (S2), which refolded S1. F3 folds have an axial plane foliation defined by muscovite and chlorite and the crenulation of earlier high-grade schistosity. They interpret all folds to have a southwest plunge but differing axial plane orientations.

Laing et al., (1978) recognised that the orebodies were originally linear in form ('surf board shaped') prior to deformation, with only relatively minor accentuation of this linearity by deformation. They also interpreted the principle macroscopic folds in the mines area to be F2 structures (the Broken Hill Synform, Hangingwall Synform and their 'Broken Hill Antiform'). The folds that have the greatest impact on the geometry of the orebodies are known as the Western Antiform and the Eastern Synform. These folds were interpreted to be F3 by Laing et al., (1978). The model proposed by Laing et al., (1978) has been the accepted model of the structure of the BH deposit since it was first proposed, however it has recently come under review, especially in its direct application to the structural interpretation of the mining field area (Webster (1993; White et al., 1995; Rothery, 2001). The application of this model to the mining field area is discussed in detail in Chapter 5.

Laing (1980) applied the informal numeric stratigraphic sub-divisions developed by the New South Wales Geological Survey to the stratigraphy of the mine leases where they are still in use (2002).

Lawrence (1967) undertook the first detailed investigation into the effects of metamorphism and deformation on the mineralisation itself and concluded that the orebody had undergone high-grade metamorphism. He agreed with Ramdohr, (1951) that the dominant ore textural type within the main orebodies (2L and 3L) was produced by solid state or annealing recrystallisation during high-grade metamorphism and named it "average type ore". Lawrence classified several "facies", of ore textural types, which he considered major textural variants, and of definite metamorphic origin. He suggested that temperatures high enough to produce sillimanite could produce partial melting ("sulphide-silicate neomagmas") within the system Fe-Pb-Zn-S and attributed the various types of pegmatitic sulphide veins that occur throughout the orebody to this process. Lawrence (1973) concluded that there was no doubt that the main orebodies had undergone substantial regional metamorphism, with two main events having affected it. The first, at granulite facies,

coincided with two stages of intense regional folding and the second, at lower amphibolite facies occurred during shearing. The major textural evidence for prograde metamorphism of the ore he listed were:

- 1) "Sulphides and silicates (including pyroxene) co-recrystallised with balanced surface tensions".
- 2) "Hedenbergite, showing no retrograde alteration, is fully recrystallised along with quartz and apatite".
- 3) "Recrystallisation of rhodonite".
- 4) "Recrystallisation of olivine-structured roepperite - at times co-recrystallised with rhodonite and with sulphides at triple junctions".

Hodgson (1967, 1974, 1975) carried out extensive work on the phase relationships of mineral assemblages established during the prograde and retrograde metamorphism of 2 Lens, with a particular emphasis on the part of the orebody around the 20 Level NBHC. He concluded that the chemical relationships of minerals and phase relationships found in sub-systems supported the view that most of the rocks formed under uniform pressure/ temperature conditions. His detailed work concentrated mostly on the minerals with the composition  $(\text{Ca,Mn,Fe})\text{SiO}_3$ , with hedenbergite, bustamite and rhodonite being the most abundant (with lesser wollastonite and pyroxmangite). He noted that pyroxmangite was abundant in the ZC area of the Pasminco Mine, but rare in the NBHC area of the same mine. He did not identify wollastonite as a separate phase in 2 Lens at NBHC but significantly, stated that it only occurred in 1 Lens when it was deformed by the Belt of Attenuation (see Chapter 5). Subsidiary minerals he identified within 2 Lens were knebelite  $((\text{Fe,Mn})_2\text{SiO}_4)$ , garnet, fluorite, apatite, orthoclase, plagioclase, biotite, pyrosmalite  $(9(\text{Fe,Mn})\text{O} \cdot 8\text{SiO}_2 \cdot \text{FeCl}_2 \cdot 7\text{H}_2\text{O})$ , gahnite and loellingite. Some important observations he made about the relationships between rhodonite and hedenbergite-bustamite were;

- 1) Rhodonite in hedenbergite-bustamite lode occurs as polycrystalline aggregates,
- 2) Any contact between massive rhodonite and any bustamite-hedenbergite bearing assemblage always has a bustamite selvage,
- 3) Sulphide vein concentrations commonly have a bustamite selvage,
- 4) Rhodonite is a minor part of hedenbergite-bustamite lode but hedenbergite-bustamite is never a part of large rhodonite bodies and

- 5) Isolated masses of pyroxene lode, surrounded by carbonate ore are generally massive rhodonite.

One of Hodgson's (1967, 1974, 1975) most significant conclusions was that the bustamite selvages, which developed between the massive rhodonite and the bustamite-hedenbergite lode, were caused by the superimposition of high-grade metamorphic phase equilibria on a lower grade metamorphic phase assemblage (i.e. after the formation of the rhodonite). Pressure/temperature conditions changed and caused a reaction between the previously stable rhodonite and bustamite-hedenbergite. He stated that the polymorphic transition from bustamite to hedenbergite (johannsenite) occurs at 830 degrees Celsius so therefore bustamite with hedenbergite must have formed at this temperature.

Maiden (1972, 1975) carried out a detailed investigation into the metamorphic features of the orebody with an emphasis on the "textural and structural features and textural changes in the ore, on a macroscopic, mesoscopic and microscopic scale". Most of his observations were of mine exposures on the 20 and 21 Levels of the Pasminco Mine. He identified most of the major structural elements of the ore and discussed many of the ore textural types and their interpreted origins producing a similar classification scheme to Hodgson (1967), and which was later supported by the findings of Webster (1993, 1994a and this study). He recognised that the 2 Lens was not a homogeneous body prior to deformation but consisted of zones that were rich in sulphides and zones that were rich in gangue minerals. Important grain relationships he noted within the ore, which showed that it had been metamorphosed were:

- 1) The minerals within the ore show polygonal relationships, with 120° triple point junctions (except for rhodonite, bustamite and wollastonite where these textures are often absent).
- 2) Poikiloblastic textures are common, especially in gangue minerals.

Maiden (1972, 1975) concluded that the coarse, even grainsize of the ore can be attributed to annealing crystallisation during metamorphism and that this process had happened several times following periods of deformation. Because the ore had recrystallised several times this texture could not be related to a particular deformation. He notes that there was some recrystallisation of sulphides during retrograde metamorphism but none in the gangue minerals so any polygonal textures in the gangue can be attributed to high-grade metamorphism.

From textural evidence, Maiden (1972, 1975) suggested a structural history of the mineralisation in which plastic flow of ore constituents during deformation obliterated all pre-existing structures on at least two occasions during granulite facies metamorphism. Maiden recognised that the manganese silicate masses were drawn out into boudins during deformation and favoured their origin as original sulphide-poor inhomogeneities in the ore (he does not seem to have recognised their original layered distribution). He interprets the banding within the ore to have formed parallel to the direction of plastic flow and interprets folding within this banding to reflect the waning stages of metamorphism where the ore became less plastic and produced flow folds rather than flow banding. He interprets pegmatitic sulphide veins and pods to have formed from residual metamorphic fluids.

Boots (1972) investigated the retrograde (upper greenschist facies) effects of metamorphism on the BH orebody (3 Lens) by examining the Browne Shaft orebody, a shear and fault bounded block of mineralisation hosted by the British Fault Zone. He concluded that deformation had caused only minor changes to the composition of the ore and showed that the lead/zinc ratio of the mineralisation pre-dated the shearing. He did note that recrystallisation had occurred in sulphide-rich portions of the ore but that silicate-rich areas were largely unchanged.

Boots (1972) recognised two major types of ore textures, which he termed prograde and retrograde. The prograde textures consisted of equidimensional grains of sulphide and gangue with common straight to slightly concave grain boundaries, triple junctions and small grains of gangue minerals commonly found at the triple junction points (textures observed by the writer in all "Stratiform" and most "Mobilised" styles of mineralisation). Retrograde types consisted of schistose sulphides and mineralisation of equigranular grainsize but in which sphalerite grains tended to be fractured, variably rounded and 'wrapped' in steely galena foliae (textures observed by the writer in mineralisation associated with late brittle faulting). He described preferential mobilisation of minor amounts of copper, cobalt and nickel and attributed the presence of silver-antimony-arsenic rich carbonate veins in fault zones to preferential mobilisation as well.

McKay (1974) documented the physical and chemical changes that occur in 2L towards its southwestern termination, describing the mineralogy and chemistry of the three most important rock types in this area; the pyrrhotite rocks, the garnet quartzite and the garnet sandstone. He also described the marginal rocks of the several of the smaller orebodies and suggested that 2 Lens was developed in areas where the underlying potosi type quartzofeldspathic gneiss is thin, and that a unit of banded iron formation was a stratigraphic equivalent to 2 Lens (see Chapter 4). He concluded that the BH mineralised system was formed in an elongate basin from volcanic exhalative processes.

### **2.2.5. 1990's to Present.**

Since the mid-1980's, only limited geological research has been carried out at BH, with most publications since that time representing accounts of work completed before 1986. Haydon and McConachy (1987) carried out a comprehensive interpretation of stratigraphic setting of the southwestern part of the BH mineralised system and its satellite mineralisation (including the Western and Centenary mineralisation, and White Leads mineralisation, see Chapter 4). This is the most detailed review of the stratigraphy of the mine leases yet published and is still used as the standard stratigraphic nomenclature by the Geology Department. Haydon and McConachy (1987) state their preference for a genetic model for the deposit involving mineralisation being deposited in clean sands.

Wright (1985) carried out a detailed facies analysis of the sedimentary environment of the orebody and concluded that normal clastic sediments of fluvio-deltaic origin hosted the orebody. Wright et al., (1987) present a detailed analysis of the sedimentary environment in which the BH orebodies were deposited and conclude that there is no volcanic component to the metasediments. They interpret the metasediments to have been deposited in a shallow prograding deltaic environment and the orebodies to form from the compactive expulsion of metalliferous brines that accumulated in reservoirs of shallow marine sands. They describe this mode of formation as "sedimentary inhalative".

Ian Plimer has carried out extensive research work on various aspects of the BH orebodies including; an investigation into the hydrothermal alteration surrounding the

orebody (Plimer, 1975, 1979), variability within the orebody in the North Broken Hill Mine (Plimer, undated internal report to North Broken Hill Ltd) and the mineralogical history of the lode (Plimer, 1984). He has supported the view that the BH deposit is a volcanic exhalite (e.g. Plimer, 1984).

In the late sixties and early seventies, several doctoral, masters and honours level projects were carried out on specific aspects of the geology of the orebodies (apart from those already discussed above). Specific examples include Billington (1973, the "B Lode complex"), Both (1970; geochemistry), Bottrill (1984; A Lode mineralogy); Burford (1972; B Lode); Ogierman (1984; structurally mobilised ore); Richards (1963; banded iron formation); Spry (1978; garnet-rich rocks); Stone (1973; quartzofeldspathic gneiss) and Woolfe (1985; mineralogy of A Lode).

Pasminco Ltd completed a reassessment of key cross sections for the BH mining field (Schuler et al., 1993). A reassessment of the regional structure of the Broken Hill Block has recently been completed by Stan White of the University of Utrecht in association with Pasminco Exploration geologists. This work has emphasised the nature and role of high grade and retrograde shearing in the tectonics of the Willyama Block and the complications they may cause for regional stratigraphic correlation (Eoin Rothery, pers comm, 1993).

Stockfeld, (1993a, b, c and d) has identified economically significant, structurally hosted mineralisation within the B Lode Horizon (see Chapter 4) that is similar in style to the "dropper" orebodies. These structures are developed parallel to the axial surfaces of F2 antiforms (particularly the NBHC Antiform, see Chapter 5).

### **2.3. DISCUSSION OF PREVIOUS WORK.**

Most previous workers have tended to focus their research on relatively small areas within the deposits, or have based their work on drill hole information. They have then extrapolated their conclusions to encompass the whole deposit. This strategy can lead to inaccurate conclusions when observations are applied to areas other than those examined. For example, the long-term geological recording by company geologists shows that the northeastern end of the BH deposit is significantly different to the southwestern end, even though there may be geological continuity and many

similarities. However, no previous studies have attempted to link a comprehensive geological reinterpretation of the deposit with an orebody-scale structural interpretation and an ore textural investigation. Such an approach allows the variations within the mineralised rocks and adjacent lithologies to be seen in context.

There are two aspects of scientific research at BH which have contributed the most to its understanding. These are; the identification of ore/gangue mineralogy (particularly visual identification) and the long-term collection of consistent, high quality geological mapping information, both underground and on the surface. Ore mineralogy was the key to defining the differing styles of mineralisation, such as 2L, 3L and the geological mapping of both regional and deposit-scale allowed the stratigraphic association of the mineralisation and the detailed geology and geometry of the orebodies to be defined. Without both these achievements, little would be understood about BH.

However, a third factor is the degree to which the deposit has been exposed by mining development. This has influenced the level of geological understanding of the BH deposit because it has influenced the ability of researchers to scientifically examine the geology of the deposit. The development of geological thinking about the BH deposit has been a process that has reflected the degree to which it was exposed by underground development, and also by the regions of the orebodies that were available for examination during any particular research project.

A related fourth factor in the interpretation of BH geology is the influence of prevailing, commonly accepted genetic and structural ideas in vogue when certain parts of the deposit were being mined and therefore available for examination. The professional backgrounds of the scientist doing the examinations of sections of the deposit that were being exposed by mining during the period of their interest has also influenced the interpretations placed on aspects of BH geology.

The outcropping portion of the orebody was a tabular body of mineralisation and hence the very first records described the orebody as a "lode". This name has persisted, even though it was shown at a very early stage that the orebody was not a simple tabular structure.



The first models are those developed in the earliest stages of mining, as the attenuated antiformal structure of the central part of the mining field was being exposed by mining and recognised. This was when the saddle reef models came into prominence (e.g. Pittman, 1892 and Jaquet, 1894)

Identification of 'crush' zones containing ore led to models of fluid conduits, delineation of the lode mineralogy and recognition of the high grade metamorphism led to models of intrusive derived mineralising fluids and magma heat sources. All these ideas tended to reflect the thinking on mineral deposits prevalent at the time (at least in the English speaking world). Ramdohr, (1951), working in Germany, provided fundamental evidence that the lode has been metamorphosed by recognising metamorphic textures in the mineralisation and showing that there is no set paragenetic sequence of ore minerals.

As the southwest and northeast plunge was recognised, and further development to depth at the southwest end of the deposit commenced, the stratiform component of the mineralisation was recognised and explained as a replacement of favourable beds, rather than just a simple saddle reef cavity infill. Various versions of this idea were developed but showed a general trend from thinking the orebody was completely replacive to increasing elements of pre-replacive features (especially the rhodonitic zones). The support for this model grew as the amount of mapping, drilling and mining exposures grew, culminating in the work of Gustafson (1939) Gustafson et al., (1950). Gustafson and his co-workers, having access to all available underground openings for mapping, virtually defined the general geology of the deposit, as it is known today.

Recognition by King and O'Driscoll (1953) and King and Thomson (1953) that the orebodies were stratiform and metamorphosed rather than replacive, came very soon after the mine geological department began underground mapping in the ZC area of the Pasminco Mine. Mapping of the disposition of the mineralisation, and recognition of the 'zinc lodes' as continuous, concordant layers was fundamental to interpretation. Once again, it was the extent of mining exposure that allowed these conclusions to be reached, as mining of some of the smaller orebodies ('zinc lode') was just beginning to take place. It is probably no coincidence that the deposit was finally shown to be stratiform from evidence gathered in the Pasminco Mine, at the southwestern end of

the field, where the 'zinc lodes' become significant orebodies. The effects of deformation are least strongly developed in this region, preserving more of the original stratiform character than elsewhere.

The conclusion by Lewis et al. (1965) that the orebody is in fact epigenetic came at a very late stage in the debate over the orebodies origins and some 12 years after King and O'Driscoll (1953) had proposed their model. This late support for the epigenetic model may reflect one of the problems that have, in the writers' opinion, plagued the interpretation of BHI geology. This is the problem of working on one part of the orebody and applying the conclusions to the entire mining field. The differences between the conclusions of King and O'Driscoll (1953) and Lewis et al. (1965) reflect the part of the orebody upon which they worked. Lewis et al. (1965) worked almost exclusively on the South Mine where the workings occupy a part of the mining field, which lies almost completely within the Belt of Attenuation. The effects of attenuation on the orebody are very severe and the clear stratigraphic relationships between ore and the surrounding metasediments have been disrupted by deformation. King and O'Driscoll (1953) were working on the least deformed part of the orebody (NBHC area of the Pasminco Mine), where the influence of attenuation is relatively slight, the 'zinc lodes' become significant orebodies, and the host stratigraphy is well preserved. A stratiform model was a far more likely development in the Pasminco Mine than it was at the South Mine for this reason.

Lewis et al. (1965) may have been hindered from recognising the extent to which the orebody in the South Mine was deformed because of a lack of available information on the textures of deformed and mobilised sulphides. Their two major pieces of evidence for the epigenetic model can be explained by post-formation deformation and mobilisation of sulphides and it has since been realised that sulphides can appear unstressed in fault zones if they recrystallise (e.g. Richards, 1966)

The position within the orebody in which work has been carried out may be the most important factor in the results attained. Work on a geological problem at the North Mine may result in very different conclusions to those gained from the same type of investigation in the Southern Operations. This may be why the epigenetic model persisted for so long with the geologists of the South Mine. Another example may be the differences between some of the conclusions of Hobbs (1966) and Laing et al (1978).

Hobbs concluded that the orebody transgressed the bedding at the North Mine, while Laing et al. (1978) working mostly to the northeast of the North Mine and later, in the Pasmaenco Mine, concluded it was conformable. The differences in their opinions may simply reflect the differences in the geology of the areas in which they worked.

The familiarity with as much previous work as is available to the writer has led him to the opinion that if early work is interpreted in terms of the position within the orebody where it was carried out (i.e. taken in context), the observations of these workers are generally valid and their conclusions can be understood in terms of the data they had to work with and should not be rejected out of hand (though these conclusions cannot be applied to the entire deposit). For example: If there has been widespread silica metasomatism within the strongly attenuated South Mine area of the orebody as has been observed in attenuated parts of several orebodies in the Pasmaenco Mine (Webster, 1993; 1994a; this study) then early conclusions about metasomatic replacement as the model of ore deposition may be valid interpretations of the evidence as seen in that mine.

To illustrate this point, observations by the writer at individual stope-scale, of the relationship between ore and the wall rocks in strongly attenuated parts of the orebody at NBHC show that the ore always truncates metasedimentary banding at a very low angle and appears dyke-like. The margins of the orebody and the adjoining metasedimentary wall rocks are intensely silicified. If taken in isolation, the above observations of ore-wall rock relationships could lead to the conclusion that epigenetic processes had structurally emplaced the ore. This region of the NBHC area (known as the southern panel) could not be used to explain the genesis of the entire orebody because it is not representative of the bulk of 2 Lens. It cannot be used to determine the structural history of the whole orebody but it is an excellent place to define the effects of one aspect of its deformation.

The observations of early workers give valuable information about the geology of inaccessible parts of the orebody. The conclusions they reached are often quite reasonable interpretations of the data that was available to them within their isolated areas of investigation. The literature has to be read at face value in the context of the part of the orebody in which it was done and allowance made for the prevailing ideas of the time.

Geological thinking and interest about BH is ongoing, as can be seen from the current exploration activity and there are large areas where the geology is little known or poorly understood. The southwestern 'zinc lode' orebodies are still open at depth in the Pasminco Mine and are currently the focus of a major surface and underground exploration effort. The northern end of the deposit is truncated by a major retrograde shear system consisting of the Western and Globe Vauxhall Shear Zones. 'Small' (greater than 1 million tonne), shear bounded blocks of mineralisation are known to be present within this system and the Lode Sequence was drilled at depth in the early 1990's to test the region; with some success.

The evolving understanding of the stratigraphy and structure of the mining field has resulted in major extensions to known mineralisation over the last three decades (e.g. the orebodies lying above 2L in the Pasminco Mine, and the Fitzpatrick Orebody). Geological models based on BH have resulted in significant exploration successes, most notably Cannington in the Eastern Succession of the Mt Isa Block (Skrzeczynski, 1993).

The large volume of research that has focussed on BH has not diminished interest in the deposit and it still attracts research. Many questions remain to be answered about BH, as is seen by the current (2002) level of differing scientific opinion that surrounds the deposit.

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## CHAPTER 3: REGIONAL GEOLOGICAL SETTING

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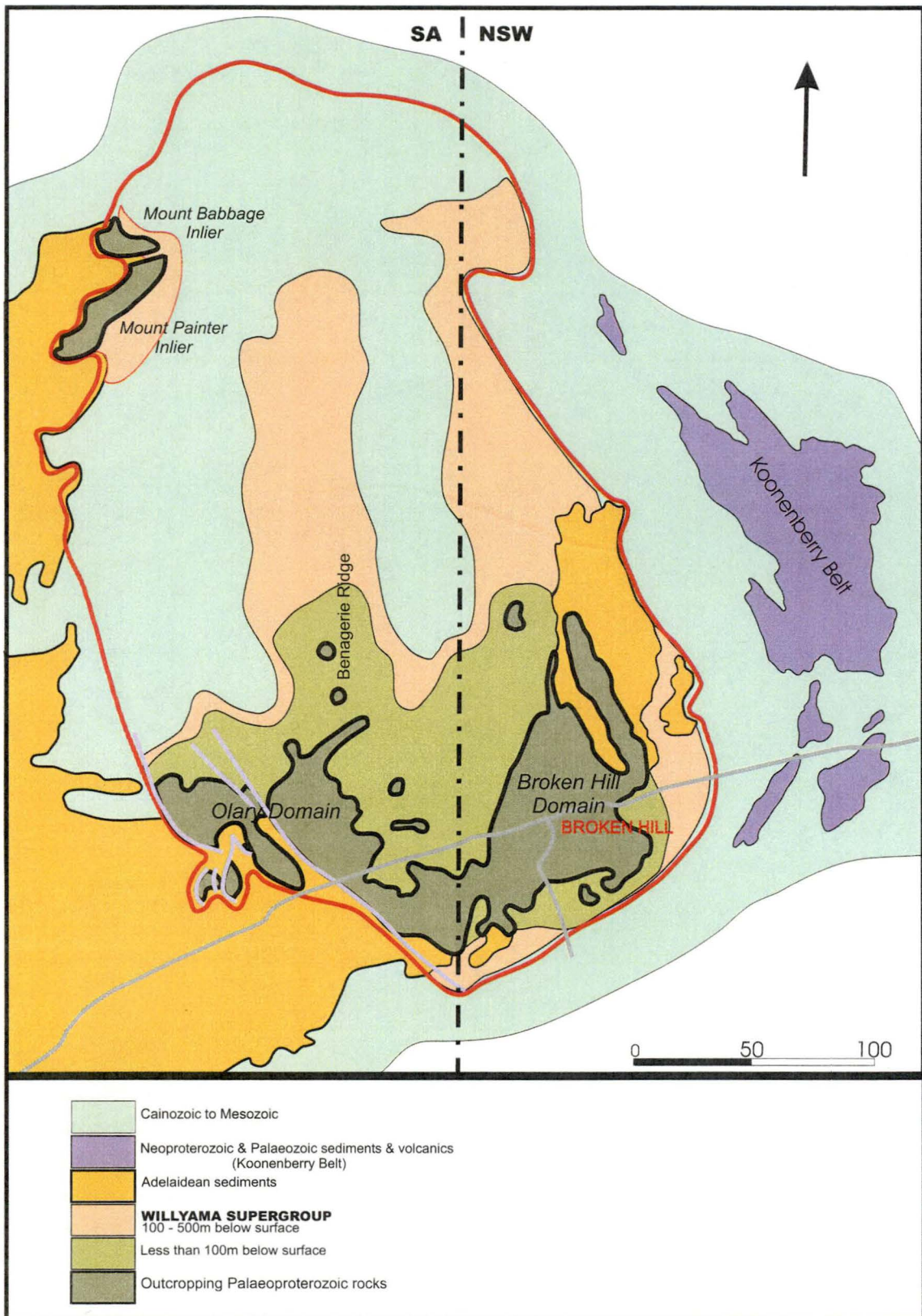
### 3.1. REGIONAL GEOLOGY AND TECTONIC SETTING OF FAR WESTERN NEW SOUTH WALES.

#### 3.1.1. Introduction.

The Broken Hill lead-zinc-silver deposit is hosted within a sequence of Palaeoproterozoic metasedimentary and metavolcanic rocks and coeval intrusives known as the Willyama Supergroup (Willis, et. al., 1983; Stevens, et. al., 1983). The Willyama Supergroup (WSG) consists of highly variable lithologies that have a long and complex history of sedimentation, intrusion, deformation and metamorphism (e.g. Willis et al., 1983; Stevens et al., 1983; Laing et al., 1978). The WSG outcrops as an arcuate belt that straddles the New South Wales-South Australian border (Figure 3.1). This chapter provides an overview of the tectonic and regional geological context of the WSG. The following summary provides an important background to the more focussed discussions about the stratigraphy of the near-ore environment and the structure of the orebodies that are presented in Chapters 4 and 5.

#### 3.1.2. Broken Hill Exploration Initiative.

Models of the strato-tectonic evolution of the Broken Hill region have received increased attention since the inception of the Broken Hill Exploration Initiative, a consortium of state and Commonwealth government agencies, in 1994 (Anderson, 2000). The new initiative has augmented the recently completed Geological Survey of NSW mapping programme that commenced in the 1970's (MINFO No 58; 1998), which covers the majority of the Broken Hill Domain. An increased understanding of the geology has resulted from new aeromagnetic surveys and collations of existing data, a deep seismic survey, systematic geochronology undertaken on key elements of the stratigraphy and systematic regolith mapping. Detailed aeromagnetic surveys have allowed outcropping stratigraphy to be traced below recent cover. A seismic transect incorporating the Broken Hill mining field has provided some insights into the deep crustal structure of the region near Broken Hill (e.g. Leven et. al., 1998a and 1998b).



**Figure 3.1.** Regional geological map of the Palaeoproterozoic to Mesoproterozoic Curnamona Province showing the extent of the outcropping and shallowly buried Willyama Supergroup. Modified after Birch (1999).

Much of the information is still being analysed and is awaiting full publication. The following discussion draws heavily on the available published results.

The accepted stratigraphy of the WSG has come under close scrutiny as a result of the BHEI and there has been an increased level of geological mapping and stratigraphic interpretation in the Olary area on the South Australian side of the border. A regional structural interpretation put forward by White et al., (1995) has spurred a re-examination of the role of shear zones in the WSG at Broken Hill.

### **3.1.3. Tectonic Setting of the Broken Hill Region.**

The Palaeoproterozoic rocks of the Broken Hill region comprise one of the most easterly outcropping Proterozoic provinces on the Australian continent (Preiss, 2000) (Figure 3.2). The rocks have had a long geological history and now form a basement to much of northeastern South Australia and large areas of northwestern New South Wales.

The Broken Hill region lies on the northeastern and eastern margin of the complex of Neoproterozoic and Cambrian sedimentary basins known as the Adelaide Geosyncline (Drexel et al., 1993) (Figure 3.2). The Palaeoproterozoic rocks formed a relatively stable basement and source area to Neoproterozoic Adelaidean sedimentation (Drexel et al., 1993). The present configuration and distribution of the Palaeoproterozoic basement in the Broken Hill region is the result of the complex overprinting of structures associated with three tectonic events; the Olarian Orogeny (-1700-1580Ma), northwest trending faults that controlled the development of the Adelaide Geosyncline (-850-570Ma) and the Delamerian Orogeny (-500Ma). The major tectonic events affecting the region are discussed further below. The combined effect within the Palaeoproterozoic rocks of the folding and faulting associated with these overprinting events produced a series of semi-isolated, partially fault-bounded blocks that outcrop as a series of inliers known as the Willyama Inliers (Thomson, 1975; Scheibner, 1976; Drexel et al., 1993). They are covered by a veneer of Mesoproterozoic, Neoproterozoic and Palaeozoic cover and are surrounded by younger mobile belts. The three main inliers are discussed further below.

The Adelaide Geosyncline and the Delamerian Fold Belt are geographically contiguous but geologically distinct. Drexel et al., (1993) define the Adelaide Geosyncline as the



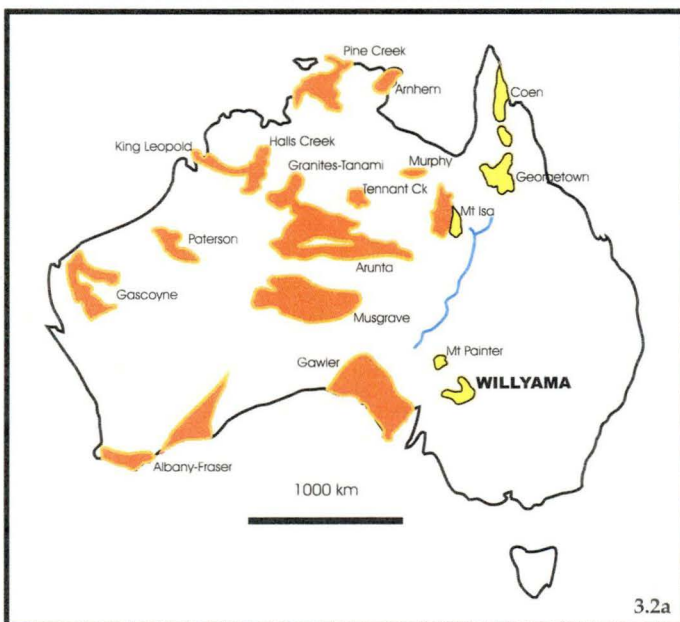
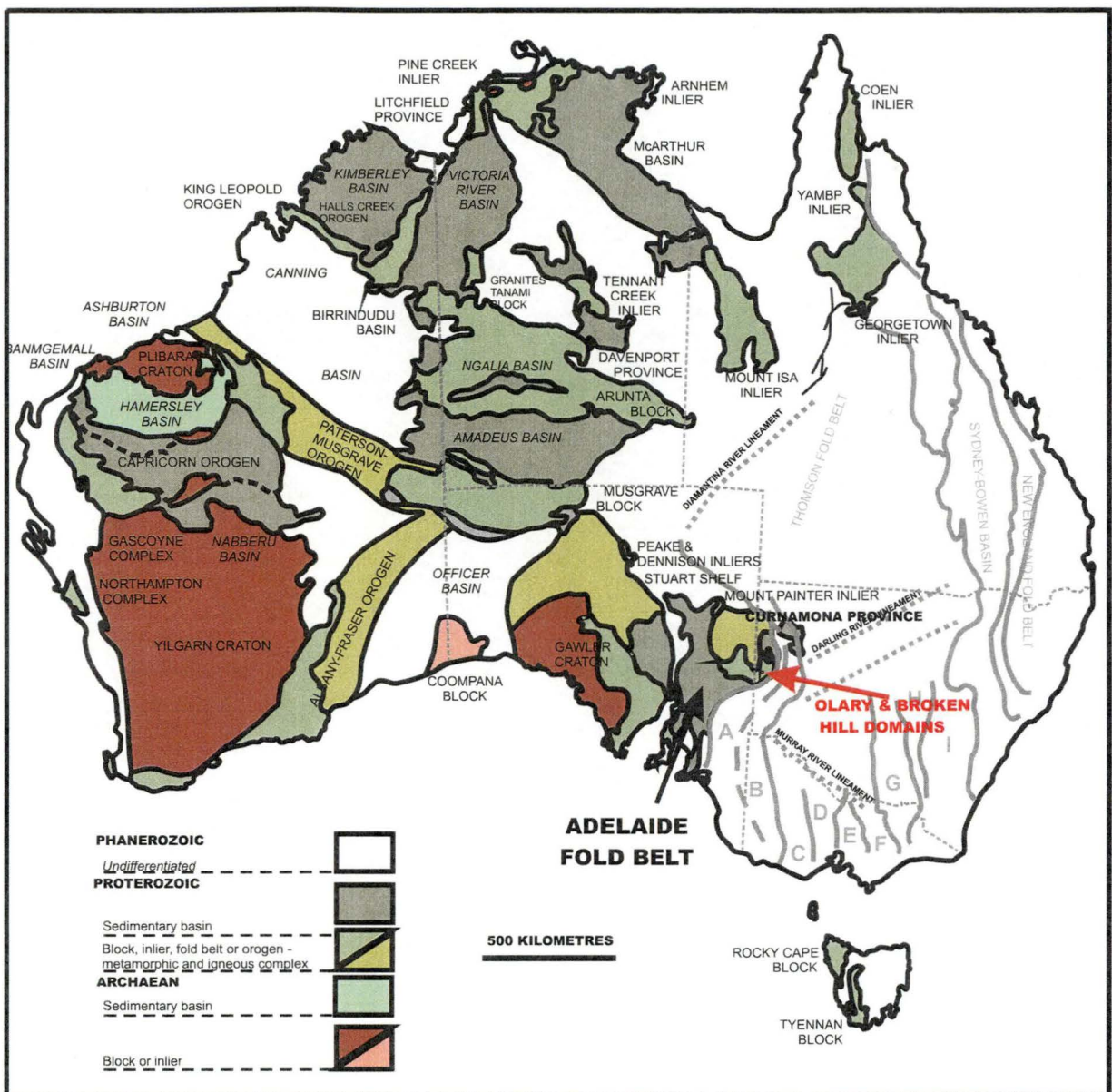


Figure 3.2. Precambrian orogens and basins separating the major Archean & Palaeoproterozoic provinces of Australia. The darker colours in diagonally divided legend boxes denote mostly outcrop, the lighter colours denote mostly sub-crop (modified after Drexel et al (1993). Also included is the tectonic framework of the Tasman fold belt system, also from Drexel et al (1993).

A = GLENELG,  
B = STAVELY,  
C = STAWELL,  
D = BENDIGO-BALLARAT,  
E = MELBOURNE,  
F = TABBERABBERA,  
G = OMEO,  
H = TUMUT,  
I = CANBERRA.

Figure 3.2a. Map of Australia showing Palaeoproterozoic and Mesoproterozoic provinces. The proposed Diamantina orogen of Laing (1996) links the Willyama and Cloncurry Terranes of eastern Australia (highlighted in yellow) on the basis of similar structural, stratigraphic and metallogenic features(modified after Laing, 1996).



sedimentary repository while they define the Delamerian Fold Belt as the area of the Cambro-Ordovician Delamerian deformation within the Adelaide Geosyncline. Other distinctions they note are that while the term Adelaide Geosyncline refers to the package of sediments deposited during the Adelaidean to Early to Middle Cambrian, the Delamerian Orogeny deformed the Palaeoproterozoic basement as well thereby affecting all three strato-tectonic units (Drexel et al., 1993).

The Delamerian Fold Belt continues to the north and west of the BH region, representing a part of the larger 850-450 Ma Tasman Fold Belt (Drexel et al., 1993) (Figure 3.2). The Delamerian Orogeny also affects the Koonenberry Belt (Mills and Hicks, 2000) that onlaps the eastern margin of the Curnamona Province (Figure 3.1) and refolds to Palaeoproterozoic basement in the mining area (Webster 1996b; this study). So the Palaeoproterozoic rocks of the Broken Hill region are encompassed by, and are partly cratonic within the Tasman Fold Belt (Figure 3.2).

To the north of Broken Hill, Proterozoic rocks of the region disappear beneath the younger cover of the Great Artesian Basin. To the Southeast of Broken Hill, the Palaeoproterozoic rocks pass beneath the Murray Basin. To the east of Broken Hill, the older Proterozoic rocks are covered by the younger rocks of the Koonenberry Belt (Figure 3.1) before disappearing below the younger sedimentary rocks of the Tasman Fold Belt. Beyond the Koonenberry Belt, lie a series of fold belts developed in younger rocks that form additional subsets of the Tasman Fold Belt System (Drexel et al., 1993) (Figure 3.2).

#### **3.1.4. The Diamantina Orogen.**

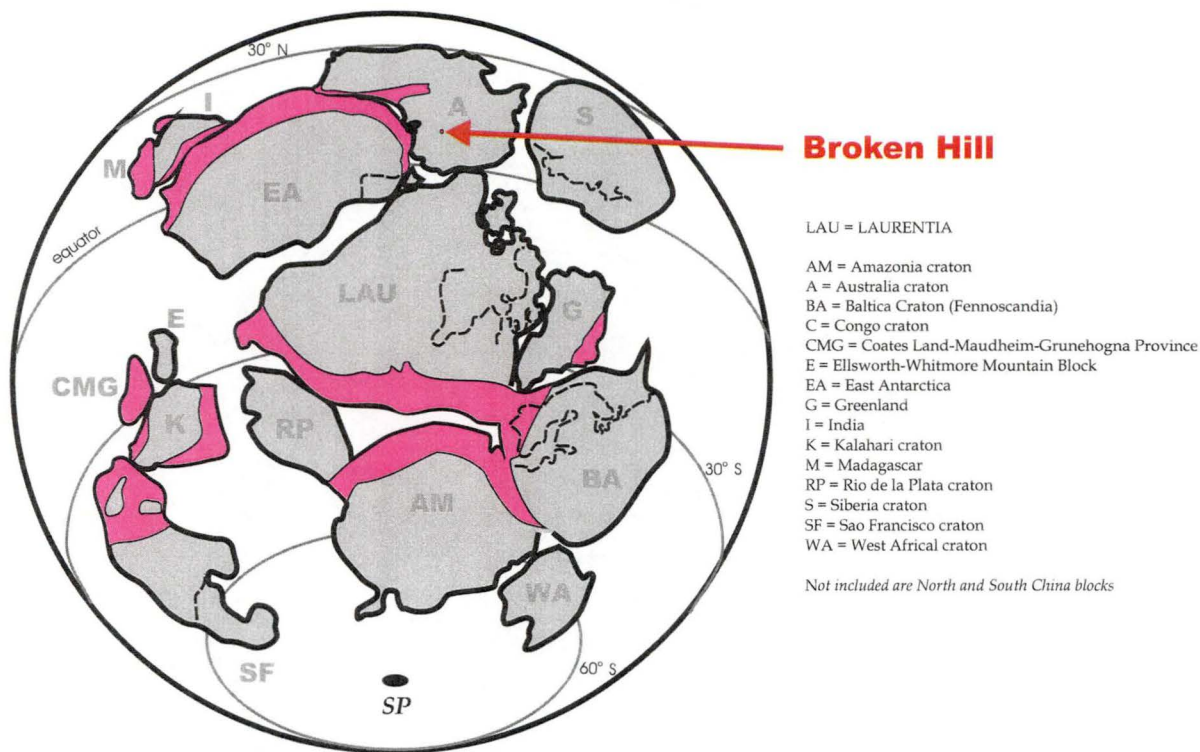
The Willyama Supergroup of the Broken Hill region has been structurally, stratigraphically and metallogenically correlated with time-equivalent provinces in northern and northwestern Queensland; the eastern Mt Isa and Georgetown provinces, by Laing (1996a) (Figure 3.2a). He interprets the close geological similarities between these provinces and encompassing sedimentation through to cratonisation, to be a result of a common orogenic event that he names the Diamantina Orogen. Laing (1996a) interprets the Diamantina orogen to represent a part of a major reworking of the crust and to be time equivalent to other such orogens elsewhere.

### 3.1.5. The Rodinian Supercontinent and the Tasman Line.

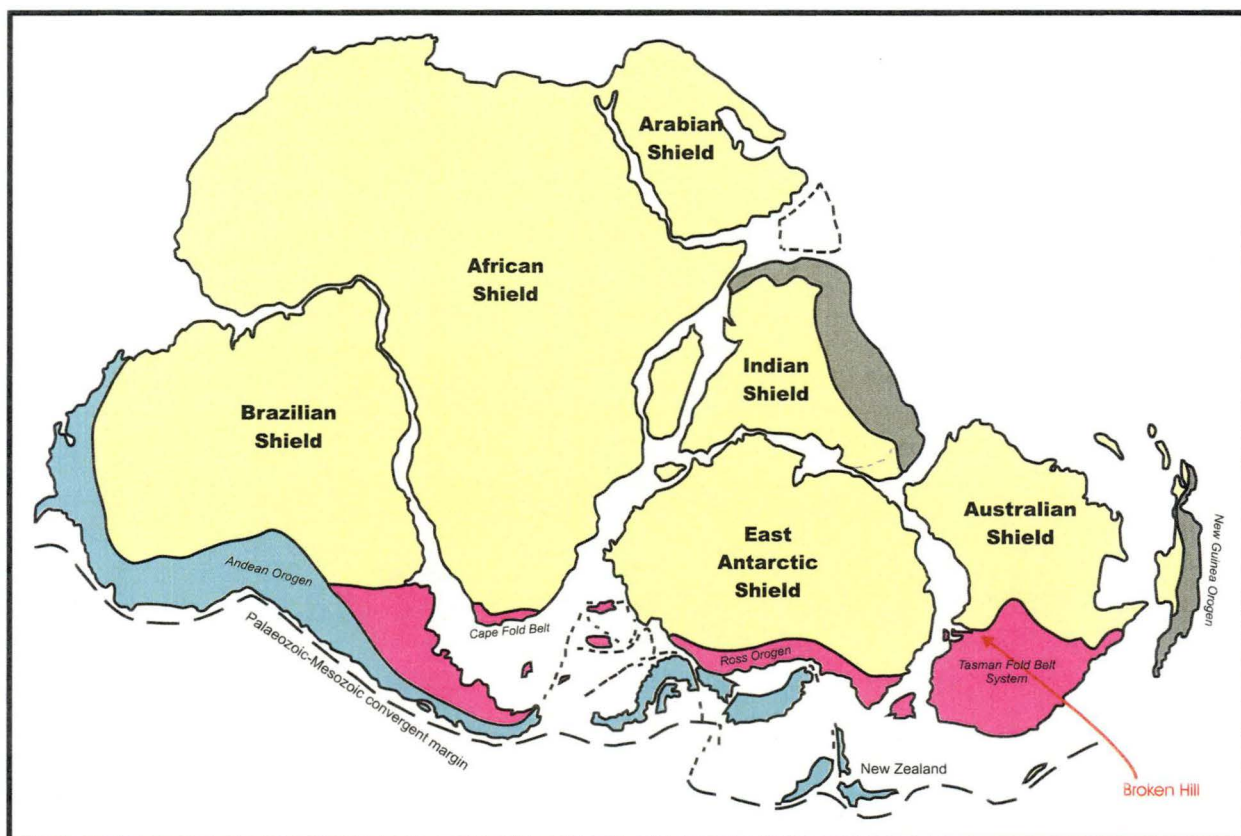
On the basis of palaeomagnetic data, Piper (1975; 1982; 1987) proposed that a long-lived Proterozoic supercontinent existed from 2500-500 Ma. This theoretical continent has become known as Rodinia. More recent reconstructions by McMenamin and McMenamin (1990) propose that, on the basis of geological evidence linking truncated Mesoproterozoic mobile belts, that the supercontinent was in fact short lived. In the latter scenario the assembly of Rodinia was marked by Grenville-aged deformation; 1.1 Ga on the margins of Laurentia, East Gondwana, Amazonia and Baltica, with the western margin of Laurentia facing East Antarctica in the so-called SWEAT (southwest U.S.A.–East Antarctica) connection. Reconstructions of Rodinia vary and research is ongoing, however one of the more recent is that of Weil et al., (1998) and is presented as Figure 3.3.

The break up and redistribution of the fragments of Rodinia commenced at *c* 750 Ma with the separation of East Gondwana from the western margin of Laurentia (Powell et al., 1993, Borg and DePaolo, 1994; Park, 1994). This rifting event and subsequent drift of the rifted elements eventually led to the amalgamation of East and West Gondwana at *c* 550 Ma (Li and Powell, 1993; Meert and Van der Voo, 1996) (Figure 3.3 & 3.4). The Willyama Supergroup (WSG) of the Broken Hill region is located just inboard of the southeastern margin of an original continental fragment of the Rodinian supercontinent and is considered to have been close to the Neoproterozoic palaeorift margin developed as the supercontinent Rodinia fragmented in the late Neoproterozoic (Gibson, 2001).

On the Australian continent, the Neoproterozoic palaeorift margin is now marked by the Tasman Line, a major structural and geophysical boundary that extends from the Tasmania to northern Queensland and marks the eastern limits of Proterozoic crust in Australia (Gibson, 1998). The Tasman Line lies to the south and east of Broken Hill. Beyond this feature to the east are the younger Palaeozoic rocks of the Lachlan and Thomson Fold Belts (Leven et al., 1998b).



*Figure 3.3 Proposed Rodinia reconstruction of Weil et al (1998). Cratons are rotated with respect to a 1010 Ma Laurentian Palaeopole. Grenvillian orogenic belts highlighted in PINK.*



*Figure 3.4 Reconstruction of Gondwana prior to break-up at -150 Ma. The position of Broken Hill is arrowed (red). Modified after Drexel et al (1993).*

## 3.2. THE CURNAMONA PROVINCE.

### 3.2.1. Introduction.

The Willyama Supergroup (WSG) (Stevens et al., 1983; Willis et al., 1983) forms a significant part of an outcropping and shallowly buried Palaeoproterozoic to Mesoproterozoic terrane known collectively as the Curnamona Province (Robertson et al., 1998) (Figure 3.1). The Curnamona Province is a “sub-circular” feature of outcropping and relatively shallowly buried Proterozoic basement rocks that extend from northeastern SA into northwestern NSW. The extent of the province is defined by areas of Palaeoproterozoic to Mesoproterozoic crust and marginal belts of late Neoproterozoic and Cambrian sediments and volcanics (Figure 3.1). Marginal Neoproterozoic mobile belts and the variable effects of Palaeozoic deformation associated with the Tasman Fold Belt mask the edges of the province while the centre is cratonic (Preiss, 2000; Mills and Hicks, 2000). The central region of the province has been cratonic since 1650 Ma and has relatively thin cover sequences of Adelaidean (Neoproterozoic), Mesoproterozoic volcanic sequences and Cambrian sequences (Robertson et al., 1998).

The Proterozoic basement of the Curnamona Province was overlapped by various Adelaidean and Cambrian sediments. The margins of the province were affected by early and middle Neoproterozoic and Early Cambrian rifting and by the Cambro-Ordovician Delamerian Orogeny. The visible edges of the province are therefore not its original edges and the Precambrian basement lies at depth beneath the mobile belts and thick sedimentary accumulations and cannot be discerned in aeromagnetic images (Robertson et al., 1998). The Koonenberry Belt, a sequence of Neoproterozoic and Cambrian sediments and volcanics, occupies the eastern margin of the Curnamona Province (Mills and Hicks, 2000). These rocks were deposited on the eastern margin of proto-Australia during and following the Rodinian break-up. The main deformation to affect the Koonenberry Belt, and impose structural trends, was the Cambrian Mootwingee Stage of the Delamerian Orogeny at c500 Ma (Mills and Hicks, 2000).

Fold structures within the Willyama Inliers can be traced northward into the central cratonic region of the Curnamona Province suggesting that the Willyama Supergroup forms the basement to the Mesoproterozoic rocks (Robertson et al., 1998).

No older basement has yet been identified below the Willyama Supergroup. However older Palaeoproterozoic and Archaean aged inherited zircons in synorogenic granitoids and detrital zircons in metasediments (Cook et al., 1994) suggest an older basement is present at depth. A recent suggestion by Nutman and Ehlers (1998) that Archaean basement might be present in the Broken Hill Domain (within the Redan Geophysical Zone) has been disproven by further SHRIMP dating (Page et al., 2000).

A recent wide-angle seismic transect conducted across the southeastern margin of the Curnamona Province has provided information about the deep crust below the Broken Hill Domain (Leven et al., 1998a and b). Modelling of the data reveals that the upper crust beneath BH is significantly thickened while the lower crust is not (Leven et al., 1998a and b). Gibson (2000a) attributes the 55 to 60 kilometres of thickening in the Willyama Supergroup to nappe formation during the Olarian Orogeny. The Moho depth ranges from 35 km on either side to 43km below the Broken Hill Block. The upper crustal layer beneath the BH Block is thickened by up to 50% while the lower crustal layer remains at a constant 14 km (Leven et al., 1998b).

Seismic data also reveals that the BH region is divided into several different structural domains by crustal-scale southeast-dipping shear zones, many of which penetrate to the lower crust (Gibson, 2000a). The exact relationship between the deeper crustal scale shears and the structures visible at surface is unclear at present.

### **3.2.2. Broken Hill and Olary Domains.**

Most of the Curnamona Province is buried under younger cover rocks (Figure 3.1). However there are large areas of exposed Palaeoproterozoic crust, mostly representing the Willyama Supergroup that outcrops as inliers on the southeastern and northwestern margins of the province (Figure 3.1). The three structurally separate southeastern inliers are known collectively as the Willyama Inliers (Robertson et al., 1998) and were named the Broken Hill Block, the Olary Block (actually a series of variably sized separate inliers) and the Euriowie Block by Scheibner (1976). The Broken Hill deposit lies in the approximate centre of the Broken Hill Block (Figure 3.1). The Mt Painter and Mt Babbage Inliers on the northwestern margin of the province comprise the Mt Babbage Domain (Robertson et al., 1998). The rocks of the Mt Painter Block may be younger than those of the Olary and Broken Hill Domains and the correlation is not firmly established (Priess, 2000), so they will not be discussed further

here. More recently, the Palaeoproterozoic inliers of the Province have been re-defined as separate but geologically similar 'Domains' known as the Olary, Broken Hill (including the Euriowie Block) and Mt Painter Domains (Robertson et al., 1998) (Figure 3.1).

The currently accepted boundary between the two domains is a linear magnetic feature striking approximately NE-NNE (Ashley et al., 1997). Additional lithological differences that have been noted across the boundary include (Crooks, 2000);

- The absence of a thick sequence equivalent to the Broken Hill Group of the Broken Hill Domain in the Olary Domain,
- The absence of a Bimba gossan equivalent in the Broken Hill Domain,
- The rarity of amphibolite sills/dykes/bodies in the Olary Domain, relative to the Broken Hill Domain,
- The rarity of c 1590 Ma "regional granites" in the Broken Hill Domain compared with the Olary Domain.

Mapping and geochronological dating have shown that the Olary and Broken Hill Domains are a part of the same stratigraphic sequence (Conor, 2000) (Figure 3.5), though correlation has been difficult, partly as a result of the limited mapping on the South Australian side of the border (Olary Domain) and partly because the two regions have slightly different geological histories (Crooks, 2000).

A firm stratigraphic correlation between the Broken Hill and Olary Domains has recently been achieved as a result of the identification of a distinctive graphitic marker unit immediately above the 'Bimba Horizon' (Olary Domain) that yielded a zircon age of  $1691 \pm 3$  Ma (interpreted to be a depositional age) that is almost identical to the  $1691 \pm 3$  Ma age obtained for a similar graphitic horizon in the Allendale Metasediments of the Broken Hill Domain (Page et al., 2000) (Figure 3.5). The firm date supports the previous interpretations of the correlation between the 'Bimba' Horizon with the Ettlewood Calc-silicate Member of the Broken Hill Domain. Details of the stratigraphic succession within the Broken Hill Domain are presented below.

## PROPOSED LITHOSTRATIGRAPHY FOR THE WILLYAMA SUPERGROUP OF THE OLARY DOMAIN

**Proposed Lithostratigraphy  
(Conor, 2000)**

<b>STRATHEARN GROUP</b>	<b>Mount Howden Subgroup</b>	Dayana Pelite
		Mooleulooloo Psammopelite
		Alconle Pelite
	<b>Saltbush Subgroup</b>	Walparuta Schist
		Plumbago Formation
<b>CURNAMONA GROUP</b>	<b>Ethludna Subgroup</b>	Bimba Formation
		Peryhumuck Cal-albite
		Whey Whey Schist
	<b>Wiperaminga Subgroup</b>	Mooleugore Schist
		Outalpa Formation George Mine Formation.

**Broken Hill Domain (Stevens et al, 1983)**

Paragon Group; Dainit Bore Metasediments
Paragon Group; Bijerkerno Metasediments
Paragon Group; Cartwrights Creek Metasediments
Sundown Group & Broken Hill Group
Broken Hill Group
Broken Hill Group; Ettlewood Calc silicate Member
Ettlewood Calc silicate or Thackaringa Group; Himalaya Formation
Thackaringa Group
Thackaringa Group
Thackaringa Group
Thackaringa Group

**Olary Domain (Clarke et al.,1986)**

Pelite Suite
Pelite Suite
Pelite Suite
Pelite Suite
Pelite Suite
Pelite Suite
Bimba Suite
Calcsilicate Suite or Quartzofeldspathic Suite
Calcsilicate Suite
Quartzofeldspathic Suite
Quartzofeldspathic Suite
Quartzofeldspathic Suite

*Figure 3.5. Proposed stratigraphic correlation between the Olary and Broken Hill Domains (after Conor, 2001). Refer also to Figure 3.6.*

### 3.3. REGIONAL STRATIGRAPHY OF THE BROKEN HILL DOMAIN.

The Palaeoproterozoic rocks of the Broken Hill Domain were formally named the Willyama Supergroup (WSG) after extensive regional mapping revealed a coherent stratigraphy (Willis et al., 1983; Stevens et al., 1983). The WSG comprise metasediments, metavolcanics and intrusives of various styles, with metasedimentary rocks ranging in age from 1710 Ma to 1640 Ma (Page, et. al., 2000). The mostly coeval S-type granitoid and iron-rich mafic tholeiite intrusives range in age from 1690-1670 Ma, (Gibson, 2000a).

Within the Broken Hill Domain, the WSG is divided into four stratigraphic groups; the Paragon, Sundown, Broken Hill and Thackaringa Groups, and also includes two gneiss-migmatite units below the Thackaringa Group; the Thorndale Composite Gneiss and the Clevedale Migmatite. The distribution of the key stratigraphic elements of the Willyama Supergroup is shown in Figure 3.6. The regional strike of the WSG is predominantly northeast-southwest and the dip is generally northwest.

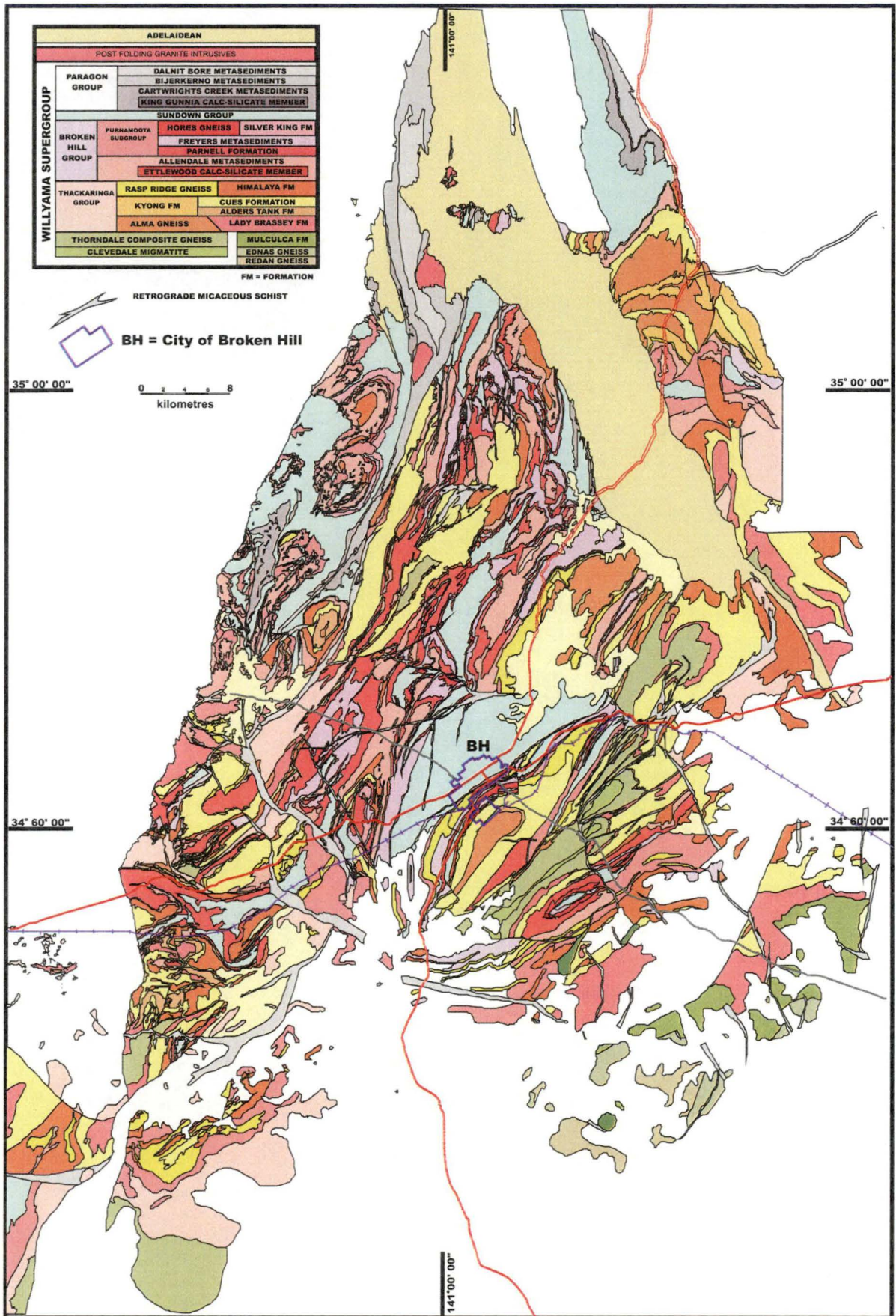
The BH orebodies lie within the Broken Hill Group (Willis et al., 1983) and some elements of the sequence recognised in the mine area as the "Mine Sequence" are located within the Thackaringa Group (see Chapter 4). The most significant units in the mining field area, and therefore the most relevant to the discussion in following chapters are the Broken Hill, Sundown and Thackaringa Groups. The Paragon Group and those units lying below the Thackaringa Group do not occur in the mines area and are therefore not discussed here. (refer to Figure 3.6 for distribution of these units in the BH Domain and Appendix 4 for brief descriptions of the units). The following descriptions are derived from Stevens et al., (1983) unless otherwise stated.

#### 3.3.1. The Thackaringa Group.

Thackaringa Group conformably overlies the Thorndale Composite Gneiss (see Appendix 4) and is characterised by diverse and distinctive quartzofeldspathic rocks. The sequence ranges from >10,000m to <30,000m thick but is usually around 1500m thick.

The group is extensively developed in the Broken Hill Domain and is sub-divided into six formations, the Alma Gneiss, Lady Brassy Formation, Alders Tank Formation, Cues





**Figure 3.6.** Geological map of the Broken Hill Domain, showing distribution of the major stratigraphic units of the Willyama Supergroup. The Broken Hill urban area is outlined in blue and marked "BH". Modified from Buckley et al. (2002).

Formation, Himalaya Formation and the Rasp Ridge Gneiss. Of particular note to the following discussion is the Rasp Ridge Gneiss, which forms a significant component of the near ore environment of the mining field. See Appendix 4 for descriptions of the sub-units of the Thackaringa Group.

### **3.3.1.1.      *Rasp Ridge Gneiss.***

The Rasp Ridge Gneiss occurs at the top of the Thackaringa Group and comprises quartz-feldspar-biotite ('granite') gneisses in several areas, including the mining field at Broken Hill. It is generally a medium-grained, quartz – K-feldspar – plagioclase – biotite gneiss with some garnet or sillimanite-rich phases. Basic and leucocratic quartzofeldspathic phases and rare Ba-rich calc-silicate rocks are often associated with the gneiss.

The Rasp Ridge Gneiss ranges in thickness from 20 to 700m and can be tabular or lenticular, regional-scale bodies that are conformable with the enclosing sequence. The top of the sequence is marked by an abrupt change to the sediments of the Broken Hill Group.

### **3.3.2.          The Broken Hill Group.**

The Broken Hill Group is the host unit to the giant Broken Hill lead-zinc-silver deposit. It is widespread throughout the Broken Hill Domain (Figure 3.6) and is in the order of 1000 to 1500m thick. The Broken Hill Group conformably overlies the Thackaringa Group and the base represents a change from the dominantly feldspathic composite gneisses of the basal Willyama Supergroup, the Thackaringa Group; Clevedale Migmatite and Thorndale Composite Gneiss, to the more pelitic facies of the Broken Hill Group, Sundown Group and Paragon Group (Figure 3.5 and 3.6).

Overall the Broken Hill Group is represented by a clastic sequence of pelitic to psammopelitic and psammitic sediments that are commonly garnetiferous and contain zoned calc-silicate nodules. The overlying Sundown Group contains sediments similar to those in the Broken Hill Group but is distinguished from it by the absence of basic and felsic gneisses and by the lack of interpreted volcanogenic units known locally as 'lode rocks'. As well as hosting the main lode, this unit hosts most of the Broken Hill-type stratiform Pb-Zn-Ag mineralisation in the district (Willis et al., 1983).

Recent U-Pb dating of zircons from the Broken Hill Group define a major metavolcanic population at 1690  $\pm$  5 Ma and is interpreted to be the age of zircon crystallisation at the time of the eruption of since-metamorphosed felsic volcanics (Page and Laing, 1992).

The Broken Hill group consists of the;

- Allendale metasediments; a basal metasediment sequence, overlain by the
- Purnamoota Subgroup; an interval of intercalated metasediments and basic and felsic gneisses and 'lode rocks'.

### 3.3.2.1. *Allendale Metasediments.*

This unit is the lowest part of the Broken Hill Group and is a predominantly metasedimentary unit composed of thinly-bedded pelite to psammopelite/psammite, minor basic gneisses, quartz-gahnite rock and tourmaline-quartz rock. In addition it contains the Ettlewood Calc-Silicate Member (described next), a well-bedded calc-silicate unit that has been correlated with the Bimba Formation in the Ethiudna Group of the Olary Domain (Conor, 2000). The Allendale Metasediments are generally 500m thick. The base of the unit is usually sharp, being marked by an abrupt change to the Himalaya Formation of the Rasp Ridge Gneiss however transitional zones are seen. The top of the unit is defined by the incoming of substantial bodies of felsic and mafic gneiss of the Purnamoota Subgroup.

### 3.3.2.2. *Ettlewood Calc-Silicate Member (Allendale Metasediments).*

This well-bedded fine to coarse-grained quartz-Ca plagioclase  $\pm$  clinopyroxene  $\pm$  amphibole  $\pm$  epidote calc-silicate rock containing high background base-metal values (Pb, Zn, W) and exists as conformable thin (0.5-10 m), elongate, tabular bodies or pods. It forms an extensive but discontinuous horizon in the Allendale Metasediments, present mainly in the northern Broken Hill Domain, Mount Robe-Belmont and Silverton-Thackaringa areas.

The unit has been correlated with the Bimba Formation of the Olary Domain and has been firmly dated at 1691  $\pm$  3 Ma (Page et al., 2000) (Figure 3.5).

### 3.3.2.3. *Purnamoota Subgroup.*

Overlying the Allendale Metasediments is an approximately 600 m thick sequence containing Fe-rich and commonly garnet or pyroxene-rich basic gneiss, felsic gneiss/rock (known as 'Potosi gneiss'), quartz-gahnite and garnet-quartz 'lode rocks' and minor to massive BHT Pb-Zn-Ag deposits. Four formations have been identified within the Purnamoota Subgroup; the Parnell Formation, Freyers Metasediments, Hores Gneiss and the Silver King Formation.

### 3.3.2.4. *Parnell Formation (Purnamoota Subgroup).*

The basal unit of the Purnamoota Subgroup is a widespread, 150-500m thick unit comprising mainly pelitic to psammopelitic/psammitic metasediments intercalated with massive to thinly layered Fe-rich, commonly garnet or orthopyroxene-bearing basic gneisses. The basic gneisses are associated with lenticular medium-grained quartz – andesine – biotite – garnet  $\pm$  K-feldspar gneisses ('Potosi gneiss') that become finer-grained quartz – feldspar – biotite  $\pm$  garnet gneiss/rock in lower metamorphic grade areas north of Yanco Glen. Relict igneous and ?fragmental textures are observed within the 'Potosi gneiss' layers in lower grade areas and in the Mt Robe-Belmont area.

Small, uneconomic BHT Pb-Zn-Ag occurrences associated with quartz-gahnite, garnet-quartz and 'banded iron formation' are widespread throughout the formation. Stratiform tungsten mineralisation is commonly hosted by tourmaline-quartz rocks and garnet-epidote-amphibole calc-silicate rocks.

In the Broken Hill mines area, the formation contains extensive bodies of basic gneiss with pelitic to psammopelitic metasediments and minor 'banded iron formation'. The upper and lower amphibolites of the "Mine Sequence" defined by Johnson and Klingner (1976) are included in the Parnell Formation by Willis et al., (1983)

### 3.3.2.5. *Freyers Metasediments (Purnamoota Subgroup).*

An interval of well-bedded pelitic to psammopelitic/psammitic metasediments occurs between the Parnell Formation and the overlying Hores Gneiss and is generally 200-300 m thick (max. 500 m). It is composed of thin, planar, rarely graded beds and sometimes containing calc-silicate nodules. In the southern part of the Broken Hill

Domain, the unit tends psammitic to psammopelitic and contains rare basic gneiss, quartz-gahnite and tourmaline-quartz rocks. In the mines area, the Freyërs Metasediments are pelitic to psammitic and directly underlie the orebodies.

The top of the formation is marked by the lower basic or felsic gneiss in the overlying Hores Gneiss or Silver King Formation.

#### 3.3.2.6. *Hores Gneiss (Purnamoota Subgroup).*

The most economically significant unit of the Broken Hill Group is the Hores Gneiss. This unit hosts the Broken Hill orebodies (Willis et al., 1983; Stevens et al., 1983) and forms a significant component of the "Mine Sequence" discussed in Chapter 4.

Hores Gneiss is 50 to 200 m thick and in sillimanite grade areas (see below) mainly consists of a medium to fine-grained quartz-andesine - Kfeldspar-biotite-garnet gneiss that is mineralogically the same as the felsic gneiss that occurs in the Parnell Formation (see Appendix 4) and is commonly referred to as Potosi gneiss. Garnets are evenly distributed and abundant. In lower metamorphic grade areas, such as that north of Yanco Glen, mapping shows that the felsic gneiss can be traced into fine-grained quartz-plagioclase – biotite  $\pm$  K-feldspar  $\pm$  garnet rock/gneiss. However, in some areas such as west of the Parnell mine, the Hores Gneiss is migmatitic and comprises blocks of garnet-bearing felsic gneiss in a coarse-grained irregular granitoid matrix (Willis et al 1983; Stevens et al; 1983).

Hores Gneiss contains varying proportions of intercalated metasediments (Willis et al., 1983; Stevens et al.; 1983) and in the vicinity of the orebodies is typically associated with minor amphibolite, tourmaline-quartz rocks that are anomalous in tungsten and rare quartz-gahnite rock. In the mines area Hores Gneiss is typically associated with minor thin but stratigraphically persistent multiple amphibolite bands, finely banded garnet-magnetite rocks (known locally as "BIF"), blue quartz-garnet rocks, thin but persistent quartz-feldspar-biotite-garnet gneiss and calc silicate horizons that may correlate with quartz-feldspar gneisses (see Chapter 4). Also at Broken Hill, the formation is anomalously rich in metasediment, consisting mainly of pelites that host the massive stratiform Pb-Zn-Ag sulphide ore bodies of the Main Lode (Willis et al., 1983; Stevens et al.; 1983).

The Broken Hill orebodies are considered to occur in a metasediment-rich part of the Broken Hill Group represented by the Hores Gneiss (Figure 3.6). However the unit has a chemistry consistent with an origin as a dacite-rhyodacite and is interpreted as volcano-sedimentary in origin. The rocks immediately enclosing the Broken Hill orebodies are also interpreted to be ultimately volcano-sedimentary in origin but deposited distal to the volcanic centre (Page and Laing, 1992). Haydon and McConachy (1987) interpret these sediments to have formed in a prograding deltaic environment with minimal primary volcanic input.

### 3.3.2.7. *Silver King Formation (Purnamoota Subgroup).*

The Hores Gneiss passes laterally into the Silver King Formation, which is distinguished by an increasing proportion of basic gneiss and metasediments. The main outcrop of the formation is in the Mount Robe-Belmont area and it is rare in the central part of the Broken Hill Domain. The unit is laterally equivalent to Hores Gneiss and conformably overlies Freyers Metasediments.

It is a 300-400 m thick formation comprising pelitic to psammopelitic/psammitic metasediments and abundant amphibolite, with subordinate lenticular bodies of quartz - feldspar – biotite  $\pm$  garnet gneiss and rock. Tourmaline-quartz rocks and minor quartz-gahnite rock occur in places.

The top of the formation is sharp change from basic gneiss to the metasediments of the Sundown Group.

### 3.3.3. **The Sundown Group.**

The Sundown Group conformably overlies the Broken Hill Group and is distinguished by the absence of basic and felsic gneisses and 'lode rocks'. It consists largely of pelitic to psammopelitic and pelitic to psammitic metasediments with occasional calc-silicate nodules and forms a relatively monotonous sequence. Well-developed bedding is present. Thin and planar and graded beds are common.

While relatively monotonous, the Sundown Group has consistent variations and grades from dominantly pelitic to psammopelitic / psammitic in the north and central



Broken Hill Domain to more psammitic to psammopelitic in the southwest, where it is thinner and not easily distinguished.

The top of the Sundown Group is defined by the incoming of the carbonaceous metasediments of the Paragon Group (see Appendix 4).

### 3.3.4. Depositional Environment of the Willyama Supergroup.

Willis et al., (1983) interpret the WSG to have been deposited in a marine environment as indicated by the widely distributed sequences of thinly bedded sediments, absence of coarse clastics and apparent lack of subaerially erupted volcanics. On the basis of whole rock geochemical analysis Slack and Stevens (1994) determined that the clastic metasedimentary input of the psammites, psammopelites and pelites of the WSG was sourced from the erosion of a mainly felsic igneous or meta-igneous rocks. They suggest that likely sources of the metasediments were the rhyolitic to rhyodacitic protoliths of local quartz-feldspar+biotite+/- garnet gneisses that are present in the lower part of the WSG, or at least from other chemically similar basement rocks in the region. Other potential sources they suggested included Palaeoproterozoic anorogenic granites and/or rhyolites in the Mt Isa and/or Pine Creek Inlier of northern Australia or the Gawler Craton of South Australia.

Intercalated with the terrigenous clastics throughout the WSG are volcanic clastics, felsic and basic volcanics, megacrystic granite gneisses and rare chemical sediments (Willis et al., 1983). Mafic gneisses in the WSG are derived from tholeiitic flows and/or sills. Exceptionally iron-rich basic gneisses are attributed to pre-metamorphic alteration within the sedimentary pile prior to metamorphism (Phillips et al., 1985). Quartz-feldspar-biotite-garnet- gneisses (Potosi type gneiss) such as the Hores Gneiss were probably formed as pyroclastic units and preserve primary volcanic textures (phenocrysts) as well as possessing a sub-alkaline rhyodacitic chemical composition (Laing 1996b). Vassallo & Vernon (2000) interpret the granite gneiss bodies, such as the Alma Gneiss and the Rasp Ridge Gneiss, to be very early, pre-deformational to syn-deformational sill-like granitoid intrusives because of the presence of porphyroclasts (former phenocrysts), intrusive relationships within gneiss bodies, metasedimentary xenoliths, microgranitoid enclaves and aplitic dykes. Calc-silicate ellipsoids and horizons of such features within the WSG have been attributed to the development of carbonate concretions during diagenesis (Stevens, 1998). Further

details of the precursors to the metamorphosed lithologies of the WSG will be presented in Chapter 4.

The WSG represents a deepening marine sequence of immature terrigenous sediments and was deposited in a developing extensional rift zone that resulted in the presence of the bimodal volcanics and extrusion of tholeiitic volcanics. The extensive depositional site was relatively shallow at commencement but subsidence continued and it rapidly deepened. Shallow shelf-like sediments gave way to sediment styles comparable with modern continental slopes. In the latter stages of deposition there was a change to lower energy sediments and a change to feldspathic sediment types (Willis et al., 1983).

The region in which the WSG was deposited was volcanically active but the depositional site was distal to volcanic activity. No proximal volcanics are present in the sequence. The region was most volcanically active during the deposition of the lower part of the sequence (Willis et al., 1983).

### **3.3.5. Challenges to the Accepted Stratigraphy.**

In the mid 1990's a reassessment of the regional structure of the Broken Hill Block was initiated by White et al., (1995). This study emphasised the nature and role of high grade and retrograde shearing in the tectonics of the Broken Hill Domain and the complications they may cause for regional stratigraphic correlation. One controversial conclusion of their structural studies in the Broken Hill Domain was that the recognised stratigraphic sequence of the WSG was not valid on the basis that it had been dismembered by a series of previously unrecognised high grade thrusts. They interpreted the Broken Hill Domain as consisting of separate, structurally distinct shear-bounded blocks and that stratigraphic correlation between the blocks was dubious and that the stratigraphy was in fact composed of thrust slices and not a sedimentary succession.

Stevens (2000) has summarised the two general concepts that have been applied to the early history of the WSG. He terms these concepts the "Stratigraphic Model" and the more recent "Thrust Intrusion Model". In the Stratigraphic Model (Willis et al., 1983), the WSG is interpreted to be an intact sedimentary-volcanic sequence deformed and metamorphosed after sedimentation ceased, with minor igneous intrusion. In the



Thrust Intrusion Model (White et al, 1995; Nutman and Ehlers, 1998; Gibson, 1998; Nutman and Gibson, 1998) the sequence is considered to be a “pseudo-stratigraphy” consisting of thrust slices comprised of metasedimentary units separated by high temperature thrusts.

Stevens (2000) argues that recent geochronological dating supports the earlier interpretation (Willis et al., 1983) of an intact sequence from the Alma Gneiss (basal Thackaringa Group) to the Dalnit Bore Metasediments (upper Paragon Group) in which only the Rasp Ridge Gneiss is out of sequence. The Rasp Ridge Gneiss is interpreted to be a sub-volcanic intrusion into the Himalaya Formation and so is not a true part of the sedimentary sequence. Stevens (2000) also observes that the present boundaries between stratigraphic units of the WSG are complexly folded and argues that if the contacts were thrusts, then they must have developed prior to folding. Pre-folding thrusts consist of “flats and ramps” he argues, and if there are ramps they must necessarily juxtapose a variety of stratigraphic units of varying ages. Yet geological maps of the Broken Hill Domains show the consistent relationship between the recognised units of the stratigraphy; Broken Hill Group is always found adjacent to Sundown Group (younger) and Thackaringa Group (older). Geochronological dating within the WSG supports the consistent age relationships between the recognised groups.

In the Pasminco mine leases, the author supervised the drilling of several diamond drill holes that passed through the basal contact of the Sundown Group and into the Broken Hill Group (e.g. DDH 3355 and 7490, see Appendix 5). This contact represents one of the major stratigraphic boundaries of the WSG and the sites of several of these drill holes was quoted as being one of the major locations of such a thrust by White et al., (1995). Detailed logging of the holes showed no sign of thrusting or even significant shearing of this basal contact and the thin ‘BIF’ unit that is commonly observed at the top of the Broken Hill Group near this contact was mostly present, even in drill holes that were 10 kilometres apart (e.g DDH 3355 and 7490). No evidence of regional-scale thrusting was observed at this contact (Appendix 5). Direct field observation by the author of the contact between the Sundown and Broken Hill Groups support the arguments of Stevens (2000). Therefore, throughout this thesis the WSG is considered to be an intact stratigraphic sequence that is largely intact.

The arguments for pre-folding thrusts in the WSG and against a reliable stratigraphic sequence that are presented by workers such as White et al., 1995; Nutman and Ehlers, 1998; Gibson, 1998 have been countered by Stevens (2000) who has shown that geochronological dating and mapping-based field observations do not support such interpretations. Stevens (2000) recognises strong evidence for large-scale thrusting that is contemporaneous with early folding events in the WSG. He also recognises that thrusting was associated with later folding events. Such thrusts may be locally parallel to earlier-folded bedding and stratigraphy but are transgressive elsewhere.

### **3.4. REGIONAL STRUCTURE OF THE BROKEN HILL DOMAIN.**

The Palaeoproterozoic rocks of the Willyama Supergroup (WSG) have a long and complex history of folding, shearing, faulting and metamorphism. The combined effects of successive overprinting deformations have produced the complex outcrop pattern of the WSG stratigraphy (Figure 3.6). In the following section, the regional structural events that produced the complex outcrop patterns of the WSG are discussed. The description of the tectonic setting of the Curnamona Province presented in section 3.1 provides a background to this section.

Laing et al., (1978) and Marjoribanks et al., (1980) recognised that the Willyama Supergroup had been deformed by at least three superimposed folding and shearing events, the first two of which coincided with prograde, granulite grade metamorphism. The third folding event was associated with retrograde metamorphism, folding and shearing. There is a significant time gap between the two main phases of deformation they recognise and they correspond to the two significant orogenic events that have affected the Broken Hill region;

- the Olarian Orogeny (1600-1605 Ma) (Stevens, 1986; Page and Laing, 1992) and,
- the Delamerian Orogen (458-520 Ma) (Marjoribanks et al., 1980; Stevens, 1986)

#### **3.4.1. Olarian Orogeny.**

Complex folding and shearing took place at granulite to upper amphibolite metamorphic grade during the Olarian Orogeny (1600-1605 Ma) imposing a strong northeast-trending structural fabric on the rocks of the WSG. The structural fabric is defined by fold axes that developed during granulite to upper amphibolite-grade

regional metamorphism (e.g. Marjoribanks et al., 1980; Stevens, 1986; Page and Laing, 1992).

Four deformational events are recognised by most workers in the Broken Hill Domain, D1 to D4 (e.g. Laing et al., 1978; Marjoribanks et al., 1980; Stevens, 1986; Laing, 1996c).

#### 3.4.1.1. *First deformation (D1).*

The regional effects of the first deformation (D1) have been interpreted in various ways but it is generally agreed that it took place during granulite grade metamorphism and imposed a regional layer/bedding parallel biotite-sillimanite-defined foliation (S1) (e.g. Laing et al., 1978; Marjoribanks et al., 1980). Laing et al (1978); Marjoribanks, 1980; and Laing (1996c) identify D1 as being associated with the development of isoclinal folds, regional nappes and nappe-thrusts that resulted in the overturning of large areas of the WSG sequence. Laing (1996c) also suggested that D1 nappe formation resulted in the redistribution of the WSG stratigraphy into domains defined by nappe limbs. The domains that Laing (1996c) defines are similar to the very large, regionally significant fold structures identified by Andrews (1922, his plate LXXIV). White et al. (1995) suggest that D1 was of a more local origin in high-strain zones and suggest that a major fold and thrust system probably formed during D2.

White et al (1995) suggested that sheath folding was at least a component of the earlier phase of deformation in the Broken Hill Domain and had produced the doubly plunging geometry of the Broken Hill orebodies. Hills et al., (2001) identified a major sheath fold in the Eldee West region of the northwestern part of the Broken Hill Domain but Neilson et al., (2001) were unsure about the nature of the same structure. The presence of sheath folds in the WSG as a part of the D1 or D2 events is therefore still uncertain.

Gibson (2000) considered D1 to be an initially low-pressure, high-temperature extensional event and that metamorphism was driven by the high heat flow caused by crustal thinning and magmatic heating.

Laing et al., (1978) interpreted the mines area to have been overturned during D1 and the stratigraphic sequence inverted. This will be discussed further in Chapter 4.

D1 was associated with anatexis and the emplacement of anatectic melts occurred throughout the event and into D2 (Stevens, 1986). In the mines area such melts formed pegmatite masses and segregations that were parallel to stratigraphic contacts. Larger masses of pegmatite are weakly transgressive of stratigraphy in the southern mines area but have a strong banding interpreted to be a D1 fabric (S1) because they are folded by later high grade (F2) folds (Webster, 1996a).

#### 3.4.1.2. *Second Deformation (D2).*

The second deformation to affect the WSG was predominantly a folding event and was responsible for the greater part of the present outcrop geometry and intense northeast-southwest grain of the region. D2 took place at granulite grade and produced mainly upright second generation fold structures that refolded S1 and S0. F2 folds range in style from tight to isoclinal folds in the southern Broken Hill Domain to broad open warps in the north). Throughout much of the southern part of the domain, F2 folds plunge to the southwest at moderate angles (Marjoribanks, et al., 1980).

The axial plane fabric developed during D2 is defined by folded flattened aggregates of fibrolite and sillimanite and by the preferred orientation of new sillimanite and biotite. It is generally only developed in or adjacent to F2 hinges and is best developed in pelitic rocks. In the northern part of the domain the F2 folds have no associated axial planar fabric and have sub-horizontal axes (Marjoribanks, et al., 1980).

#### 3.4.1.3. *Third Deformation (D3).*

During the third deformation (D3) the WSG underwent widespread retrogression and shearing (Stevens, 1986). D3 is marked by the onset of regional retrogression and was developed across the domain in equal intensity. The event is characterised by the development of a vertical muscovite - chlorite +/- biotite schistosity (S3) that, at its highest grade, may also contain sillimanite. S3 developed axial planar to small and large-scale moderately open folds (F3).

In the mines area, two distinct phases of D3 are recognisable, termed D3A and D3B by Webster (1996a) and Morland and Webster (1998). D3A is recognisable as relatively narrow (2 to 30 metres) but intense zones of relatively high grade shearing, transposition, attenuation and localised small-scale associated folding that have had a

significant effect on the F2 fold geometries and the geometry of the orebodies. A later phase, D3B, is typified by the development of quartz-sericite-biotite shearing, usually in association with zones of D3A shearing. While the development of the two stages is a continuum, the latter phases of shearing are characterised by initially biotite-rich shears and then relatively narrow quartz-muscovite-biotite shearing (Webster, 1993; 1994a; 1996a).

### 3.4.2. Delamerian Orogeny.

Deformation associated with the Cambro-Ordovician Delamerian Orogeny (458-520 Ma) has affected the margins of the Curnamona Province and had significant effects within the Willyama Supergroup (WSG). Stevens (1986) recognised these effects as being mainly seen in the overlying Neoproterozoic Adelaidean cover rocks but also manifested in the Palaeoproterozoic basement as a resetting of isotopic systems, reactivation of Olarian shear zones and possibly the intrusion of dolerite dykes and plugs and later zoned pegmatites.

#### 3.4.2.1. *The Fourth Deformation (D4).*

While Stevens (1986) considered the WSG to have been cratonic during the Delamerian Orogeny, Webster (1996b) considered that gentle refolding (F4) of the basement had taken place, producing dome and basin structures throughout the Broken Hill Domain and gently refolded the orebodies along a NNW-SSE axis. Additional evidence in support of Webster's (1996b) view is presented in Chapter 5.

D4 was associated with a second period of retrogression in the WSG (Stevens, 1986). Dolerite dykes intruded into mineralisation were also altered and dismembered by plastic flow in the sulphide-silicate rocks and some hydrothermal activity occurred along faults and shears (including alteration of the dykes). The hydrothermal activity produced laminated fault and vein sets within the orebodies and the Thackaringa style of galena-siderite-quartz veins were formed within re-activated shears. Temperatures reached within faults were locally high because the pyroxenoids rhodonite and bustamite were crystallised in localised occurrences within fault zones (Webster, 2000b).

On the basis of investigations in the Southern Cross area, to the north of Broken Hill, Wilson and Powell (2001) recognised that deformation became progressively localised into high strain zones in the WSG over time. The result was the formation of D2 shear zones with highly strained fabrics separated by less strained D2 zones preserving D1 fabrics.

### **3.5. REGIONAL METAMORPHISM.**

The sedimentary, volcano-sedimentary and intrusive rocks of the Willyama Supergroup in the Broken Hill region have undergone metamorphism to produce intense local and regional partial melting in metasediments, formation of low pressure granulites and retrogression (Phillips, 1978).

#### **3.5.1. Thermal Events in the Curnamona Province.**

Primary Industries & Resources South Australia (2001) recognise the following thermal events in the Curnamona Province;

- c1720 - c1700 Ma; felsic event, A-type volcanics and high level intrusives
- c1690 - c1680 Ma; mafic intrusives and perhaps extrusives, S-type volcanics and high level granites with which the Broken Hill deposit is associated,
- c1640 - c1630 Ma; I-type granites of the Olary Domain
- c1600 Ma; peak metamorphism, ranging from granulite facies grade in the south (e.g. Broken Hill) to greenschist facies in the north (e.g. Dalnit Bore and Benagerie Ridge)
- c1590 - c1580 Ma; major influx of S-type granite, primarily in the Olary Domain.
- c15??- c15?? Ma; granite dominated, bimodal magmatism forming the volcanics of the Curnamona Province, and the granites of the Mounts Painter and Babbage Blocks in the Northwest.

#### **3.5.2. Regional Metamorphism.**

Regional metamorphism varies through the Olary and Broken Hill Domains (Figure 3.7a), from andalusite grade in the northwest to granulite grade in the southeast (Phillips, 1978). Four metamorphic zones are defined on the basis of pelitic and mafic assemblages (Phillips, 1978);

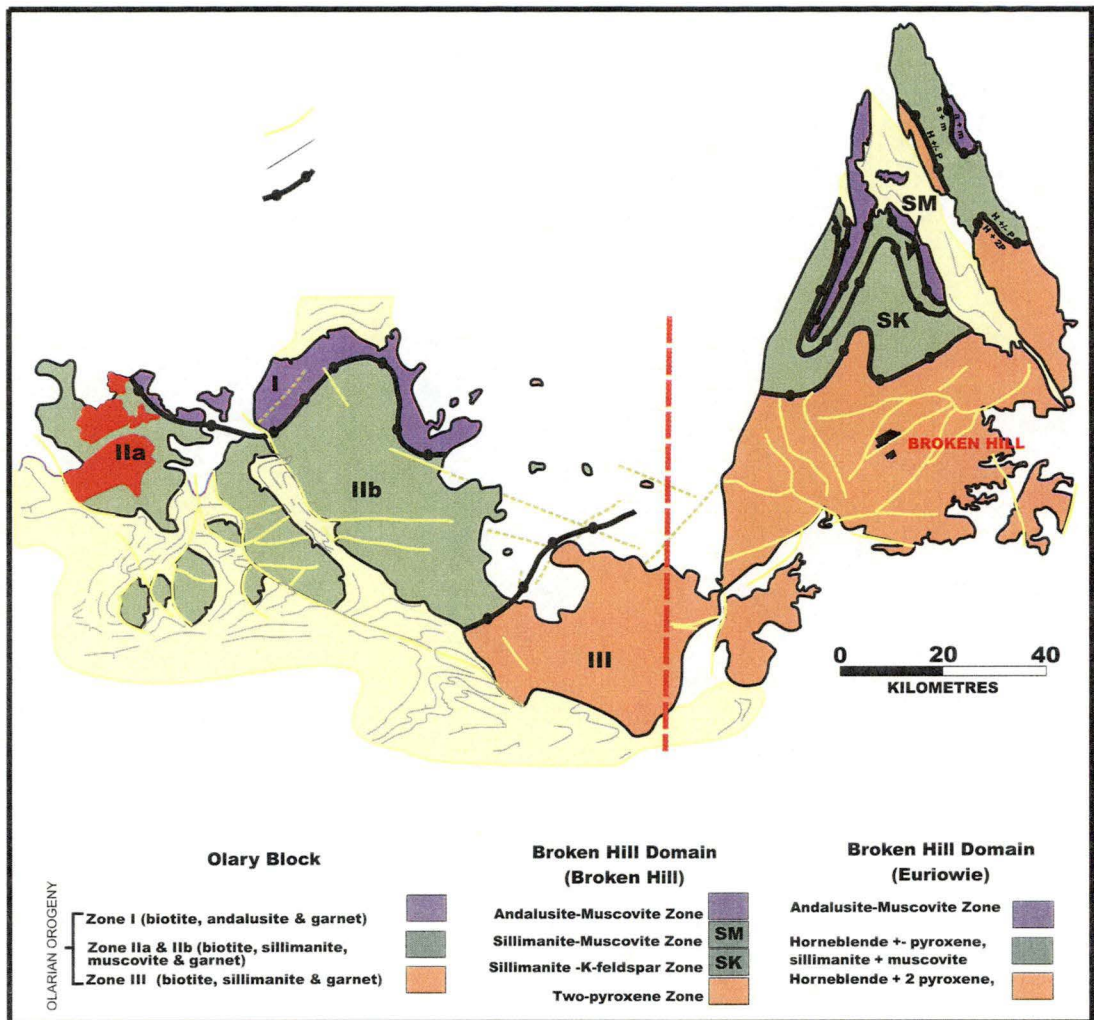


Figure 3.7a. Variation of metamorphic grade across the Olary and Broken Hill Domains (Modified after Drexel et al (1993) and incorporating information from Laing (1996).

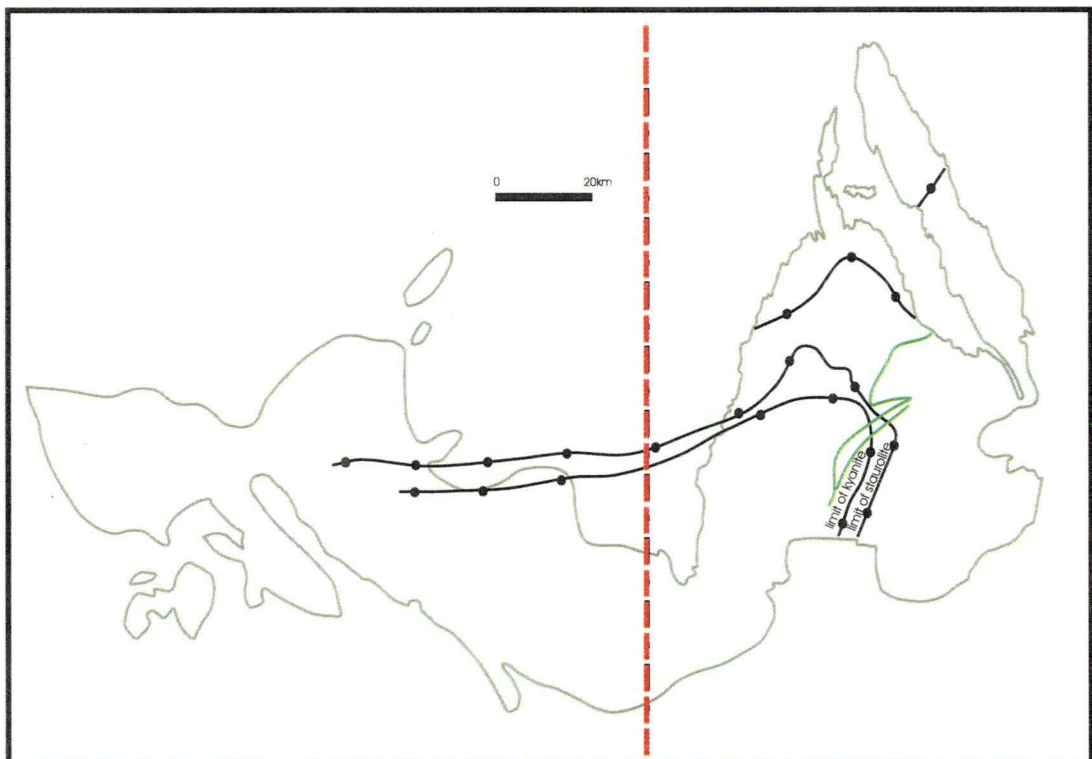


Figure 3.7b. Retrograde metamorphic zones in the Broken Hill & Olary Domains (modified after Laing, 1996a)

- Andalusite-Muscovite
- Sillimanite-Muscovite
- Sillimanite-K-feldspar

The BH orebodies lie within the two-pyroxene zone, in the centre of the Broken Hill Block (Phillips, 1978).

The Olarian deformation (D1, D2 and D3) took place under granulite to amphibolite conditions (M1) but persisted throughout the waning of the event and greenschist grade retrogression accompanied the final phase of D3 (Marjoribanks et al., 1980; Hobbs et al., 1984; Webster, 1996a). At the peak of M1, granulite grade temperatures reached approximately 800°C and a pressure of 550 Mpa, equivalent to 20 km of burial (Phillips, 1978; Stevens, 1986).

The D4 Delamerian deformation took place during a thermal pulse that reached 350°C and, in the WSG, low grade metamorphism (M2) was concentrated in shear and fault zones and their immediate surrounds. Temperatures within localised zones of intense deformation may have surpassed 400°C, reaching metamorphic grades sufficient to produce plasticity in the gneissic rocks and allow drag folding to develop in fault zone margins and plastic flow to dismember dolerite dykes in sulphide-silicate-sulphide rocks of the orebodies. More widespread regional warping probably took place within the WSG. High temperature hydrothermal activity also took place in fault zones. Pyroxenoids, rhodocrosite and siderite were deposited in open space fills and as layered veins in laminated vein systems associated with fault zones, and dolerite dykes were garnetised in ore masses (Webster, 1996b; 2000b).



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## CHAPTER 4: DEPOSIT STRATIGRAPHY

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### 4.1. INTRODUCTION.

In this chapter, the stratigraphy of both the near-ore sequence and the mineralised complex of orebodies and companion lithologies is described and re-evaluated. This is done in the light of a comprehensive geological reinterpretation of the major mine levels (presented as digital maps on the CD in Appendix 1). Integral to the discussion is a description of the stratigraphy of the mineralised environment, particularly the distribution and geometry of visually and geochemically distinctive 'lode rocks' and key marker units of the host sequence. Such units provide an important means of defining the structure of the gneiss package that contains the orebodies and for defining the stratigraphy, geometry and structure of the mineralised system itself.

An understanding of the stratigraphy of the near ore environment is considered important to the present study for the following reasons:

- Stratigraphic marker units are useful for the structural interpretation of high-grade gneiss packages, such as those that host the BH orebodies, including the definition of medium and large-scale folds and shear zones;
- A detailed knowledge of the geometry of the orebodies, distinctive companion lithologies and marker units within the mineralised system provides information about the architecture of the deposit. It also provides a basis for determining the effects of deformation on the geometry of the mineralised zone;
- Geological interpretations of successive mine levels allow down-plunge changes in the geometry of key units and orebodies to be identified. If the effects of deformation are so defined, they can be 'removed' and the form of the original mineralised system restored;
- An understanding of the stratigraphy of the host sequence provides a framework for the control and efficient design of exploration drilling, mine resource definition drilling, near-mine exploration and regional exploration;
- The lithological associations between mineralised rocks and surrounding stratigraphy provide a guide for exploration in analogous terranes, and
- A detailed knowledge of the geology of the entire deposit provides a firm basis for the development, or re-assessment of, genetic models for the BH deposit.

To the authors' knowledge, there has been no attempt to undertake a compilation of the geology of the entire orebodies at mine-scale since that of Gustafson (1939); upon which the present study draws heavily. There have been few attempts to relate the structural and stratigraphic features of the wall rocks to the comparable features within the orebodies and mineralised environment (possible exceptions are Hodgson, 1967; Maiden, 1972; Boots, 1972 and Webster, 1993; 1994a). Attempts to delineate the geometry of the near-ore host-rock units (such as 'lode rocks') based on mine mapping data are rare, despite the significance that is given to these rocks in genetic models. This study attempts to redress these omissions and to examine the stratigraphic and structural relationships between the wall rocks, the mineralised rocks and their associated lithologies.

The primary aim of this project was to resolve problems in the ore lenses (section 4.7, below). The review of the more extensive Mine Sequence draws heavily on a widely scattered literature and unpublished drilling, with the addition of the authors own data, to resolve discrepancies in previous descriptions. A single summary such as this cannot do justice to the complex details of this package. Further work is required to complete the interpretation of this extensive, complex and economically significant package.

Surface geological mapping provides the most comprehensive and detailed information about the stratigraphic succession within the central part of the field, so key sources of mapping have been compiled into a single map sheet (Figure 4.1, in separate map folder). This map provides the basis for much of the first half of the following discussion. Additional information about the near-mine stratigraphy is derived from unpublished underground geological mapping (including that of the author), mine cross sections and the cross sections presented in Gustafson (1939); Gustafson et al., (1950; 1952) and Schuler et al., (1993). These sources, particularly the latter, allow the compilation of level plans such as those presented as Figures 4.2 and 4.3 (in separate map folder), and the addition of stratigraphic information to the geological map compilations in Appendix 1.

The second part of this chapter describes the geology of the orebodies and their companion rocks in some detail, focussing on the results of the present geological interpretation.

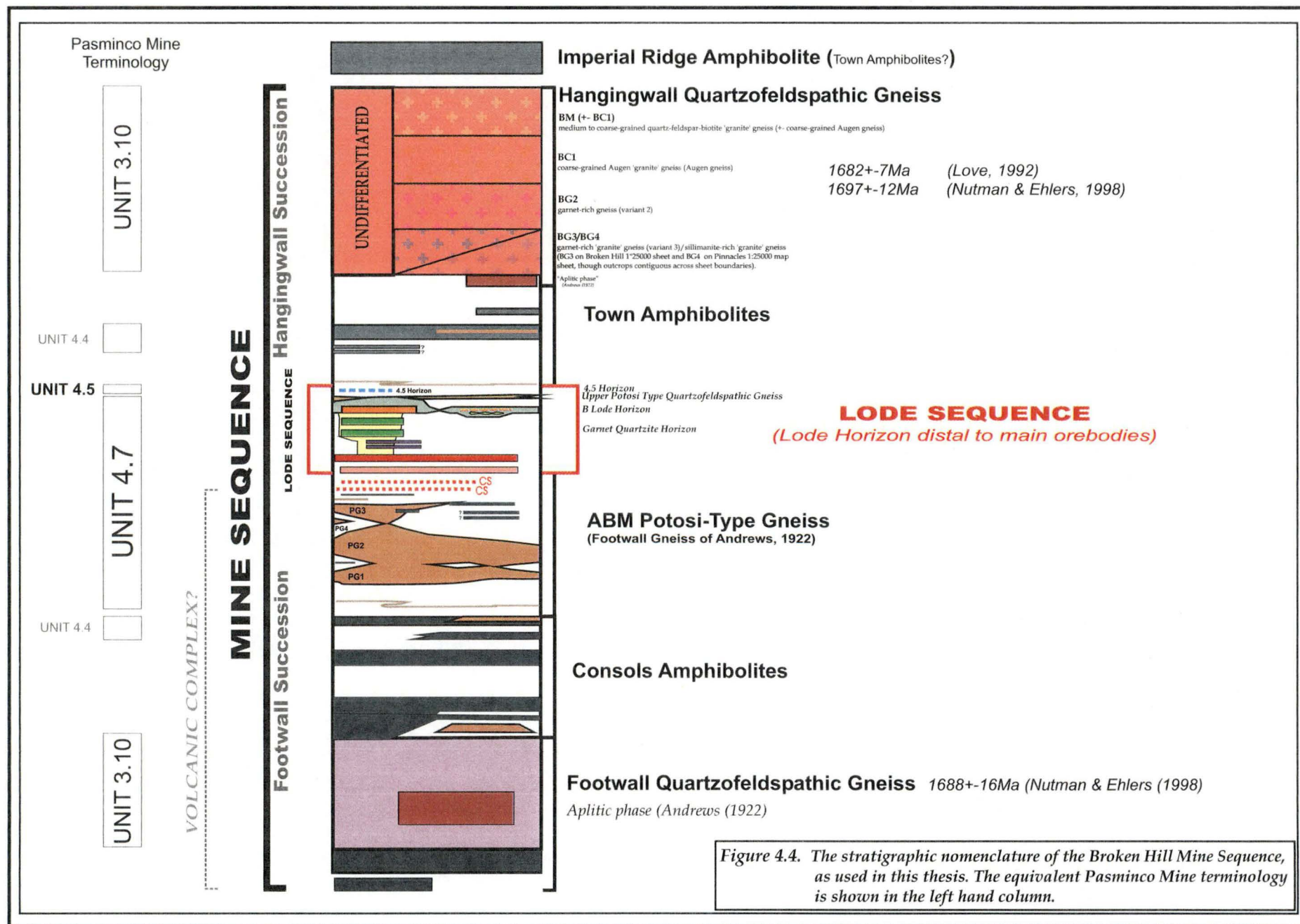
## 4.2. THE MINE SEQUENCE.

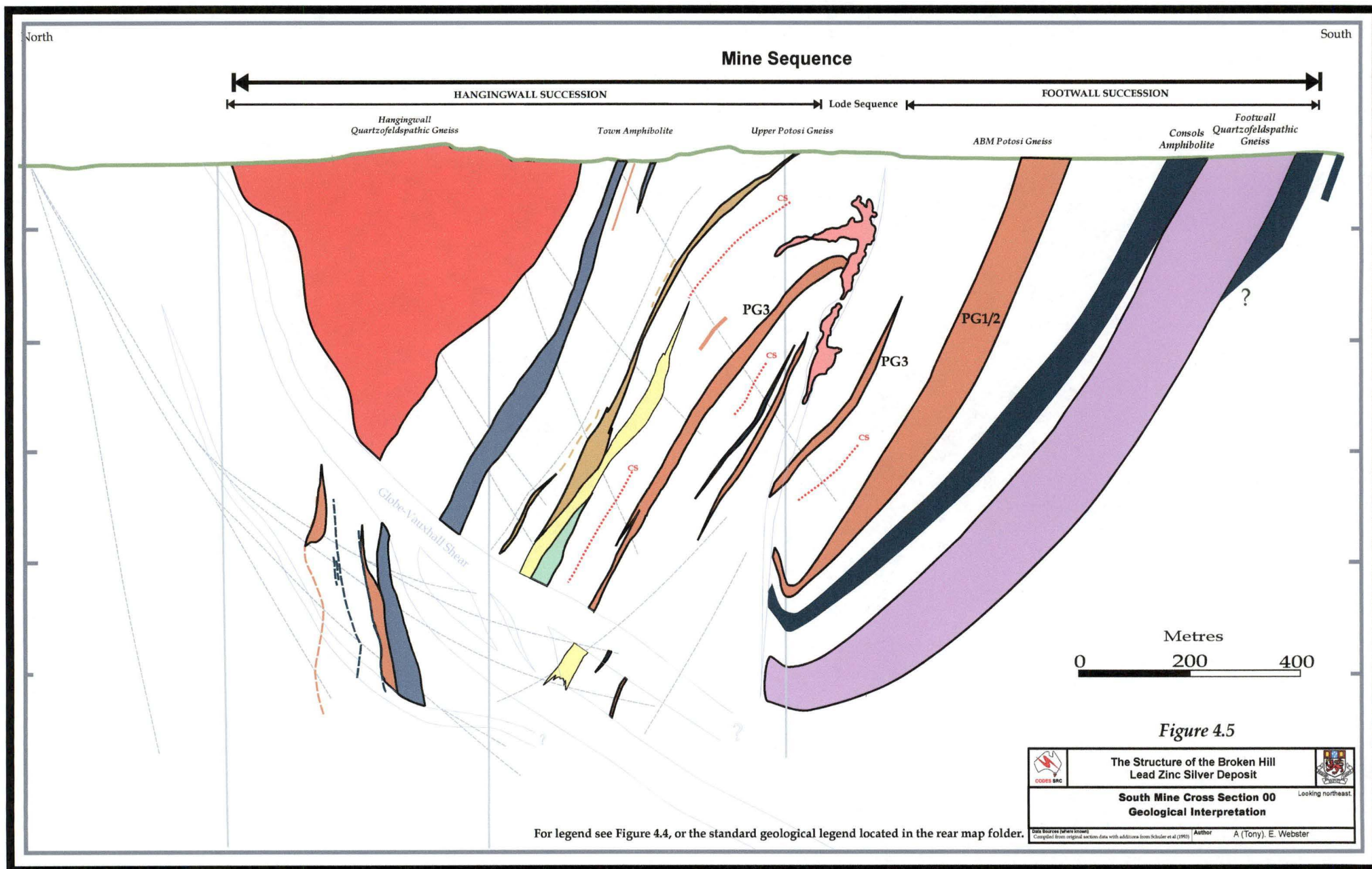
### 4.2.1. Introduction.

The Broken Hill orebodies are hosted within a distinctive package of gneissic rocks that was informally named the "Mine Sequence" (MinSeq) by Carruthers and Pratten (1961) and Johnson and Klingner (1976) (Figure 4.4). Most units of the MinSeq are formally assigned to the Broken Hill Group, with some Thackaringa Group elements (Willis et al, 1983), and it forms a particularly diverse interval in the transition from the predominantly feldspathic composite gneisses of the Thackaringa Group to the predominantly pelitic facies of the Broken Hill Group and upper Willyama Supergroup (Stevens et al., 1983).

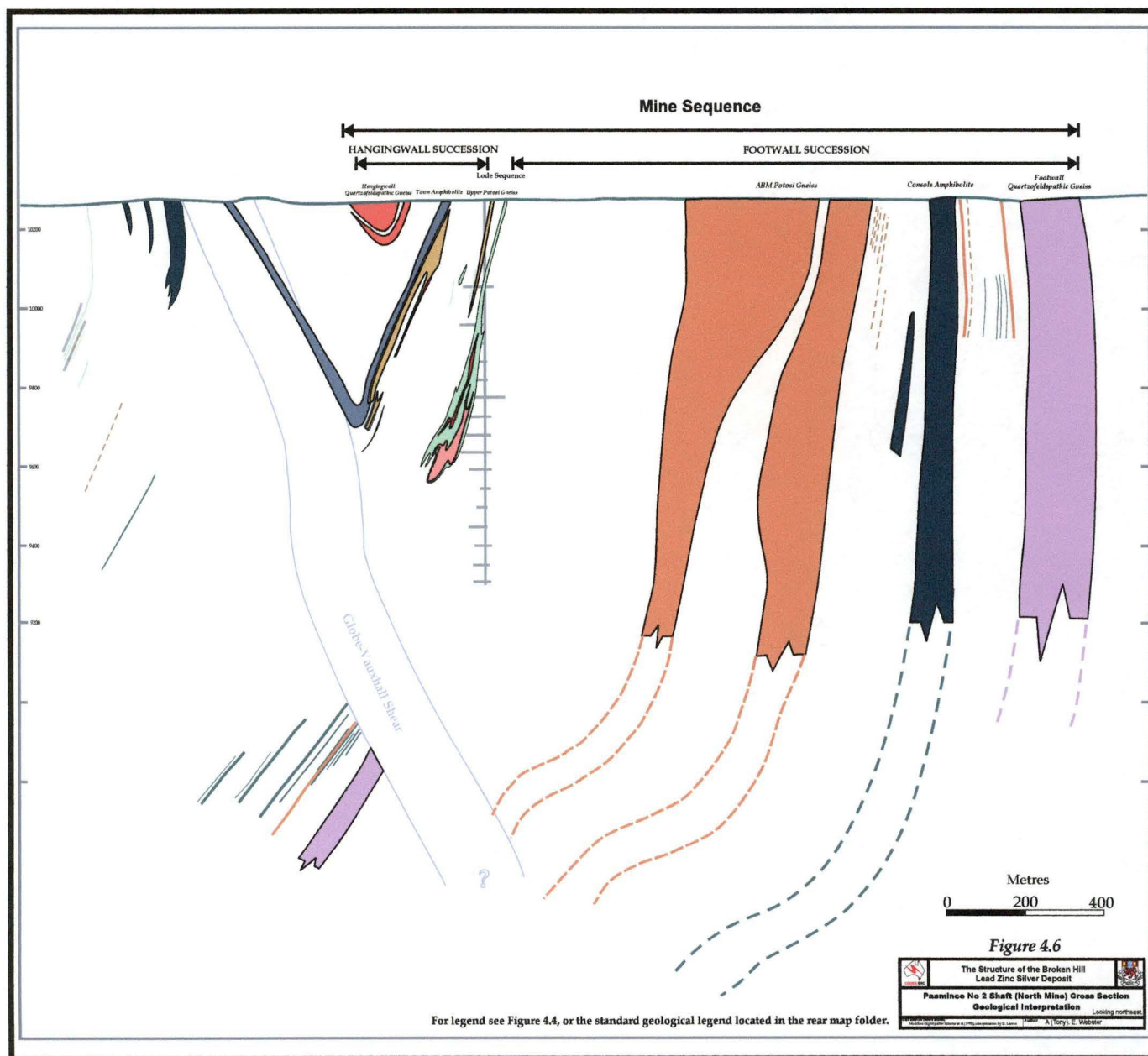
The MinSeq outcrops as a northeast-southwest trending arcuate belt extending from Kelly's Creek in the southwest to Stephen's Creek in the northeast; a strike length of 27-kilometres (Johnson and Klinger, 1976, Morland and Webster, 1998). On a regional scale, the sequence arcs from a southerly strike in the region of Kelly's Creek to an almost easterly strike in places northeast of the city (Figure 4.1, in separate map folder). It ranges in thickness from approximately 2 kilometres to less than 100 metres, becoming markedly thinner in the immediate near-ore position. The sequence dips steeply north to northwest throughout the mining field except locally, on short limbs of mesoscopic folds (Figures 4.5 and 4.6). The MinSeq is known to a depth of 2.5 kilometres on the mine leases because of exploration drilling (Carruthers and Pratten, 1961; Carruthers, 1965; Johnson & Klingner, 1976, Larsen and Webster, 1996, Morland & Webster, 1998). The MinSeq was interpreted to be overturned by Laing et al., (1978) and Haydon & McConachy (1987), but for the purposes of this study, the sequence is considered to be continuous, the right way up and north facing, as was suggested by Carruthers and Pratten, (1961) and Johnson and Klingner, (1976).

Within the MinSeq, there are several key marker horizons (Figure 4.4) that have been recognised since the earliest days of mining (e.g. Marsh, 1893; Jaquet, 1894; the Scientific Society of Broken Hill, 1910) and the stratigraphic succession was first formally defined and described by Andrews (1922) and Browne (1922). From Andrews' (1922) work, greatly expanded upon by Gustafson (1939) and Gustafson et al., (1950, 1952) and by the mostly unpublished work of company geologists, a host succession to the BH orebodies was identified and its details defined. Further









definition of the sequence has come from industry geologists including Henderson (1953; 1956); King and O'Driscoll (1953); Carruthers and Pratten (1961); Gentle (1968), Johnson and Klingner (1976) and Haydon and McConachy (1987).

The uppermost and lowest units of the succession are thick quartzofeldspathic gneiss units (Carruthers and Pratten, 1961). In this study, they are named the Footwall Quartzofeldspathic Gneiss (southern or lowermost unit) and the Hangingwall Quartzofeldspathic Gneiss (northern or highest unit) (Figure 4.1 and 4.4). The boundaries of the MinSeq are defined as follows;

- The upper boundary is defined by the top of the Hangingwall Quartzofeldspathic Gneiss and,
- The lower boundary is defined as the bottom of the lowest amphibolite unit of the several that lie immediately below the Footwall Quartzofeldspathic Gneiss.

Between the bounding quartzofeldspathic units the MinSeq is characterised by a package of pelitic to psammitic metasediments interspersed with more or less lenticular members comprised of varieties of quartzofeldspathic gneiss, amphibolite, and other distinctive units, including calc-silicate horizons, magnetite-bearing pelites and thin banded iron formations (BIF). These members are to be described in the following sections. The members do not represent formal stratigraphic units but marker horizons. Often, the lithologies of interest are repeated at multiple levels and part, or all, of some may be intrusive.

A variety of other distinctive lithologies occur in the mineralised environment and are spatially associated with orebodies and sub-ore sulphide occurrences. The distinctive companion lithologies are known locally as "lode rocks" and are described further below (section 4.4). Individual units of the MinSeq are described in sections 4.3 to 4.5 below. A summary of the interpreted precursors of the major rock types of the MinSeq is presented in Figure 4.7.

In-mine and mine lease exploration and development activity in the mine leases by North Mine, Zinc Corporation and Pasminco geologists over many years has confirmed the stratigraphic succession described by Andrews (1922); Gustafson (1939) and Carruthers and Pratten (1961), and has further refined the details of the sequence. It has shown that the broad framework of the MinSeq stratigraphy is remarkably continuous along its strike length throughout the BH mining field and into the proximal extensions of the mineralised system to the northeast and southwest

**Figure 4.7.** Suggested precursors of key lithologies of the Mine Sequence. Modified after Haydon & McConachy (1987).

Author	Pelites & psammites	Quartzofeldspathic gneisses			Palaeoenvironment
		Granite gneiss	Potosi gneiss	Amphibolites	
Sutherland (1891)	Sediments				Evaporitic fluviolacustrine, saline alkaline
Andrews (1922)	Mudstones & sandstones	Acid igneous intrusions	Acid igneous intrusions	Basic igneous intrusions	Marine-relatively far from shore
Stillwell (1922)	Mudstones & sandstones	Acid igneous intrusions	Sediments	Basic igneous rocks	
Gustafson et al. (1950)	Clays, sandy clays, sands	Granitic sills	Calcareous sand stone	Basic sills	
King & Thomson (1953)	Argillites & arenites	Sediments	Sediments	Sediments-lava Flows	
Thomson (1954)	Shales & sands	Blanket arkoses	Calcareous graywackes	Dolomitic sediments	Intracratonic basin-un stable shelf & miogeosyncline
Condon (1959)	Sediments	Sediments	Sediments		Unstable shallow marine Shelf
Thomas (1960)	Argillaceous & arenaceous sediments	Arkosic sediments	Lime-bearing shale	Impure dolomite	Major transgressive-regressive sedimentary cycle -
Carruthers (1965)	Sediments	Arkosic sediments with possible volcanic component	Graywacke or calcareous shale	Basic intrusions volcanics with admixed sediments	
Richards (1966)	Shales & sands	Feldspathic sediments, graywackes	Sediment with tuffaceous volcanic component	Basic tuffis, lavas, sills -	Volcano-sedimentary
Mackenzie (1970)	Shales & sands	Acid volcanic (rhyolite)	Acid volcanic (rhyodacite)	Iron-rich basaltic tuff	Geosynclinal environment with mixture of sediments & volcanics
Johnson & Klingner (1975)	Shales & sands	Acid volcanic (rhyolite)	Acid volcanic (rhyodacite)	Basic volcanic (basalt)	Volcano-sedimentary
Stanton (1976)	Tuffaceous sediments	Silty to sandy rhyodacitic detritus	Dacite or dacitic tuff	Basaltic to andesitic tuff	Shallow-marine volcano-sedimentary regime characterized by block faulting & rifting
Plimer (1979)	In part volcanoclastic sediments	Altered acid pyroclastics with admixed sediments	Rhyodacitic tuff	Basaltic lava, tuff, or tuffite	Volcano-sedimentary
Willis et al., (1983)	Turbiditic terrigenous sediments	Felsic volcanics	Felsic volcanics	Basic volcanics	Developing volcanically active rifted zone- shallow unstable environment to stable deepening marine environment
Laing et al., (1984)			Rhyodacitic ash falls & ignimbrites		Volcano-sedimentary environment distal from volcanic activity
Herriman (1984)	Detrital sediments	Arkose	Arkose from deeply weathered basic parent	Basic volcanic	High-energy deltaic
Haydon & McConachy, (1986)	Sediments		Immature clastic sediment		Prograding clastic wedge-deltaic
Stevens et al., (1998)		Granite, volcanic (lava or ash flow), or a mix of the two	Volcanic or volcanoclastic, not intrusive.		If granite gneiss intrusive, it was emplaced conformably during sedimentation only 1-1.5 km below sea floor



(Johnson and Klingner 1976; Larsen and Webster 1996). In detail, the lithologies occupy relatively constant positions. Despite the evolution of complex structural models for the mines area (e.g. White et al., 1995), the recognised MinSeq stratigraphy has successfully provided the framework for exploration in the mine leases for the last 80 years.

A consistent MinSeq stratigraphic succession is recognisable despite the varying degrees of structural complexity and significant textural variations within most rock types due to local variations in structure, metamorphism and composition. Discontinuities are observed within most key units, which pre-date the earliest recognised deformations. Such features are interpreted to be depositional variations or reworking (erosion) in the Palaeoproterozoic. Various degrees of structural complexity within the MinSeq have been suggested by several workers (e.g. Laing et al., 1978) but have not been supported by detailed investigations (e.g. Haydon and McConachy, 1987; Webster, 1993; Morland and Webster, 1998) (see Chapter 5). Some of the constituent marker units are thinner in the immediate ore environment. The Potosi-type quartzofeldspathic gneisses (see section 4.2.2 below) in the footwall of the orebodies are dramatically thinner in the immediate near-ore environment but form thickened elongate 'lenses' just to the south of the ore zone. However, all of the recognised stratigraphic elements of the MinSeq are present throughout the mining field, with, perhaps, a tendency to be better developed and defined in the southwestern and central areas of the field. If the quartzofeldspathic gneiss units are discounted, the MinSeq retains a relatively consistent thickness of between 100 metres and 250 metres over a strike length of over 10 kilometres.

The MinSeq is particularly well understood in three regions of the field where extensive diamond drilling has taken place. These areas include the Pasminco Mine and southern leases, the northern side of CML 7 and ML 1249 (at depth) where drilling targetted the Western and Centenary Mineralisation (e.g. Figure 4.5), and on the Pasminco northern leases, in the Potosi mine area and Silver Peak prospect (see section 4.7.11).

The stratigraphic sequence of the southwestern end of the orebodies and Pasminco southern leases has been well described by previous workers (e.g. Carruthers and Pratten 1965; Johnson and Klingner 1976; Haydon and McConachy, 1987; Schuler et al., 1993). Haydon & McConachy (1987) have described the sequence through the Western

Mineralisation within the central part of the mining field but the drilling they used as sources did not extend to depth below the main orebodies in the central part of the field. Henderson (1956) described the stratigraphy of the North Mine and northern leases and pointed out the difference in the MinSeq to that described in the southwest. Schuler et al (1993) presented a cross-section-based compilation of the MinSeq stratigraphy through the entire Line of Lode.

Despite the high level of understanding of the MinSeq succession, the stratigraphy of the near ore environment is poorly defined in large tracts of the mining field. Within the area of the Central Region (South Mine/Block 14 mines), there is little drilling and development beyond the immediate ore production openings. The stratigraphy of the near ore environment in the North Mine is mostly known from drilling on key sections, and underground development in areas away from the orebodies is restricted. Most stratigraphic information about the central core of the mining field is derived from surface mapping (Jaquet, 1894; Andrews, 1922; Gustafson, 1939), some open pit mapping and from widely spaced regional or shaft cross sections that have been the focus of work to define the ore environment (Figures 4.1, 4.5 & 4.6). There are approximately 12 such cross sections through the deposit, most recently re-compiled in Schuler et al., (1993). The stratigraphy to the immediate south (mine grid east) of the orebodies is also poorly defined at depth due to sparse drilling and mine development. The gaps in the knowledge about the near ore stratigraphy of the MinSeq hamper the clear delineation of fold and shear structures in some parts of the mining field. It therefore inhibits the determination of whether the folds and shears affecting the mineralisation also affect the surrounding rocks in comparable ways.

#### **4.2.1.1. *Mineralised Horizons in the Mine Sequence.***

Several mineralised horizons have been recognised within the MinSeq, the most significant of which were referred to as the Upper Lode Horizon; the Main Lode Horizon (North Mine, unpublished data); the Rasp Ridge Lode Horizon (Carruthers and Pratten, 1965; Johnson and Klingner, 1976) and the Burke Street Mineralisation (Pasminco Mining, unpublished data). More recent structural and stratigraphic interpretations interpret the Upper and Main Lode Horizons to represent the same mineralised stratigraphic unit (the Lode Horizon; see section 4.4), which has been complexly folded and is repeated on both limbs of an F2 synform (Laing et al., 1978, Pasminco Mining, unpublished data). The Bourke Street Mineralisation has also been

shown to be the structurally repeated Lode Horizon lying on the northern limb of the same synform (the Hangingwall Synform; see Chapter 5) (Laing et al., 1978; Pasminco Mining, unpublished data). An additional mineralised horizon has been identified between the Lode Horizon and the Rasp Ridge Lode Horizon on the Pasminco Southern Leases (Pasminco Limited, unpublished data). It represents an intermediate, weakly developed psammite-hosted zone of Unit 4.5-like mineralisation that cannot be correlated with either the Lode Sequence or the Rasp Ridge Lode Horizon and lies between them (Pasminco Limited, unpublished data) (Figure. 4.8).

#### **4.2.1.2. *Metasediments of the Mine Sequence.***

The focus of the following discussion will be on the more unusual marker units of the MinSeq. Therefore, the variably bedded and layered psammite, psammopelite and pelite that comprise most of the MinSeq are not described. In general, it can be said that bedding and graded bedding are well preserved in many parts of the near ore sequence (e.g. Figure 4.10a). The sedimentary progenitors of the important metasedimentary rock types in the Mine sequence are listed in Figure 4.7. Metasediments also form an important component of many of the units described here. Because they are not distinctive, they have been treated superficially.

For descriptions of the metasediments within the MinSeq, the reader is referred to Stevens et al., (1983); Willis et al., (1983); Haydon and McConachy, (1987); Stevens et al., (1988) and Wright et al (1993). For a comprehensive analysis of the sedimentary environment of the Broken Hill mines area, refer to Wright et al., (1993).

#### **4.2.2. *Potosi-Type Quartzofeldspathic Gneiss.***

Since the early work of Andrews (1922), a distinctive type of quartzofeldspathic gneiss has been recognised to form stratigraphic marker horizons within the MinSeq and is known as Potosi Type Quartzofeldspathic Gneiss (commonly referred to as "Potosi gneiss" in Broken Hill). This rock type features prominently in the following discussion, so is described here.

The Potosi gneiss is a quartz-feldspar-biotite-garnet gneiss of distinctive appearance and outcrop pattern, which was first described by Browne, (1922) in an appendix to Andrews, (1922). It is a medium to fine-grained quartz, feldspar and biotite gneiss that



is characterised by a distinctive texture in which equant garnet porphyroblasts are rimmed by (or often replaced by) black biotite and occasionally feldspar, giving the rock a 'spotty' texture. Small convoluted and often ptlygmatically folded pegmatite veinlets occur throughout. It is characterised by low alumina and relatively low calcium and iron (Johnson & Klingner, 1976; Haydon & McConachy, 1987). It forms several important stratigraphic marker horizons in the MinSeq on both the hangingwall and footwall of the orebodies and is a dominant constituent of the Lode Horizon beyond the main mining field.

The type locality was near the main shaft of the former Potosi Mine (since removed by open cut mining), located immediately to the northeast of Imperial Ridge and to the northwest of Round Hill on the Pasminco Northern leases. "Potosi Gneiss", as defined by Browne, (1922), was largely confined to the hangingwall of the orebodies; specifically to the narrow unit that lies to the north of the mining field and which is named the "Upper Potosi Type Quartzofeldspathic Gneiss" in this thesis (section 4.4.3.5). He described it as forming; *"a narrow intrusion traceable on the hanging-wall side of the lode from White Leads up through Broken Hill quite close to the Great Lode on the hanging-wall side, northeastward past De Bavay's works, and past the Potosi and Silver Peak Mines as far as the Globe and Consolidated mines. It is a good example of a narrow, persistent sill."* The first analysis of "Potosi Gneiss" was conducted on a specimen from a locality in a *"creek just south east of Potosi Mine"* (Browne, 1922, table of analyses, p 324). Andrews, (1922) never specifically refers to "Potosi Gneiss" in his monograph but uses the term "granulites".

A much thicker occurrence of Potosi gneiss occurs in the footwall (south) of the orebodies (Figures 4.1, 4.2 and 4.3). It was named the "Alma Footwall Gneiss" (or more simply, "Footwall Gneiss") by Browne, (1922) and is referred to in this thesis as the "ABM Potosi-Type Quartzofeldspathic Gneiss" (see section 4.3.5). The "Footwall Gneiss" was recognised to be similar to the "Potosi Gneiss" by Browne, (1922), however he considered the latter to be distinguishable in hand specimen by a generally finer grainsize and more felsic character. The distinction was so definite that Browne, (1922) recognised distinct occurrences of "Potosi Gneiss" within the upper part of the "Footwall Gneiss". According to him, the most prominent such occurrence is located on the upper margin of the main "Footwall Gneiss" outcrop to the south of the British Mine, near the Menindee Road. Andrews, (1922) showed such a zone in a similar

position within the "Footwall Gneiss" in his surface map, immediately to the south of the South Mine (Figure 4.1, in separate map folder).

Browne, (1922) considered that the "Potosi Gneiss" zones within the 'Footwall Gneiss' outcropped more prominently, forming a *"bar of hard, compact gneiss that resists weathering rather better than some of the typical Footwall Gneiss"*. He also suggested that thin section examination of slides revealed other areas within the "Footwall Gneiss" that were similar in texture to "Potosi Gneiss" and suggested that it probably occurred elsewhere within it.

Since the 1954 decision by the Zinc Corporation geology department to formally merge the two classifications under one name, this distinctive gneiss has been known under the collective term of "Potosi-Type Gneiss" (Zinc Corporation unpublished memorandum, 1954) and the northern and southern units have generally been regarded to be the same structurally repeated lithology (e.g. Laing et al., 1978). Most workers since Gustafson et al., (1950) have disregarded the differences between the two main occurrences of this rock type at BH. The northern and southern occurrences of Potosi gneiss are generally considered correlates that are structurally repeated (Gustafson, 1939; Gustafson et al., 1950; Laing et al., 1978; Haydon & McConachy, 1987). Yet, even workers who correlated the "Footwall Gneiss" with the "Potosi Gneiss" acknowledged the differences between the two lithologies (e.g. Gustafson et al., 1950).

Recent workers have emphasised the similarities between the various occurrences of Potosi gneiss adjacent to the mining field and several have correlated them (e.g. Laing et al. 1978; Haydon & McConachy, 1987). However, early workers were sure of the difference between these rock types, a view that is adopted in this thesis.

#### 4.2.3. Sub-divisions of the Mine Sequence.

For the purposes of this study, the MinSeq is divided into three litho-stratigraphic packages, based on the close spatial association between units and their stratigraphic position relative to the main orebody position. They are named the:

- Hangingwall Succession,

- The Lode Sequence (host sequence to the most significant mineralisation in the MinSeq), and the,
- Footwall Succession.

The following sections describe the stratigraphic sub-divisions of the MinSeq that are used in this thesis (sections 4.3-4.5). The discussion of the succession is organised from the base to the top of the host sequence of the orebodies (south to north).

The structural repeat model of Laing et al., (1978) has resulted in nomenclature system that merges lithological descriptions of units that are considered here to be separate (e.g. the Pasminco Mine stratigraphic nomenclature, Figure 4.4) and has made it difficult to determine which published descriptions of some units apply to northern or southern parts of the sequence. A key example of this is the present Geological Survey of New South Wales classification of the Rasp Ridge Gneiss, which incorporates large bodies of quartzofeldspathic gneiss on the southern and northern sides of the orebodies (see section 4.3.1 below). So, wherever possible, descriptions of units have been found that relate to a known locality.

### **4.3. THE FOOTWALL SUCCESSION.**

#### **4.3.1. Introduction.**

The Footwall Succession of the MinSeq extends from the base of 3 Lens (or the Garnet Quartzite Horizon in the southwest Pasminco Mine) to the base of the Footwall Quartzofeldspathic Gneiss (section 4.3.2). It outcrops throughout the southern margin of the mining field, forming a belt extending from the Pasminco southern leases to the northern leases. It is significantly thinner beneath the orebodies in the Pasminco Mine (see section 4.3.6).

#### **4.3.2. Footwall Quartzofeldspathic Gneiss.**

The Footwall Quartzofeldspathic Gneiss (FQG) is the lowermost unit of the MinSeq (Figure 4.4, 4.1, 4.2, 4.3, 4.5 and 4.6). It is classified as Rasp Ridge Gneiss by the Geological Survey of NSW (Stevens et al., 1983; 1988).

The FQG outcrops to the south of the mining field and extends for a strike length of over 19 kilometres, in an arcuate belt trending south through northeast, and extending from Kelly's Creek in the southwest to Piesse's Nob/Stephens Creek Reservoir in the northeast. In the centre of the mining field, it trends northeast-southwest (Figure 4.1, in separate map folder). The thickness of the FQG ranges from 60 to 180 m for much of the mining field but greatly increases to approximately 700m north of the DeBavay Shear, reaching its maximum thickness of approximately 1,200m adjacent to the Stephens Creek Reservoir where it occupies the hinge of the Broken Hill "Synform" (see Chapter 5).

The unit has been intersected at depth throughout the mining field by drilling and by underground development in the Pasminco Mine (e.g. Figures 4.3, 4.4, 4.5). It has also been intersected at depth in the Pasminco Southern Leases (Cross Section 226), in the central part of the field (e.g. BHS Section 3000N and 6000N), on the No 2 Shaft Cross Section (Figure 4.6) and in the Pasminco Northern Leases (Schuler et al (1993). In all locations in the mining field, the FQG is a relatively thin and strongly planar unit.

The FQG consists of a platy, medium to coarse-grained quartz, feldspar (orthoclase and oligoclase), biotite gneiss with garnets locally (Carruthers and Pratten, 1961). Garnet is commonly abundant in the upper part of the formation and in such locations it resembles Potosi gneiss. This is an important observation as it suggests a stratigraphic and compositional relationship with the overlying ABM Potosi Type Quartzofeldspathic Gneiss described below (section 4.3.5). There is no obvious consistent textural difference between the FQG and the Hangingwall Quartzofeldspathic Gneiss (section 4.5.3), which are often correlated (e.g. Laing et al., 1978); except that the FQG is generally platier and often resembles Potosi gneiss. In addition, the HWQG is usually coarsely gneissic, with well-developed augen of feldspar and elongate garnet porphyroblasts (Carruthers & Pratten, 1961; Johnson and Klingner, 1976). The FQG contains hornblende-bearing gneisses in some places (e.g. Stevens et al., 1998).

The outcrop habit and general unit morphology of the FQG is distinctive, defining a planar tabular unit of great strike length, contrasting with the HWQG, which forms a thickened lenticular mass that is internally zoned and more 'pluton'-like (Figure 4.1, Figure 4.4). Stevens (1988) described an outcrop of the FQG that occurs at the western end of the railway cutting near the Menindee Road grain silos, in the northeastern part



of the mining field. It consists of medium to coarse-grained quartz-feldspar-biotite gneiss with a very well developed gneissosity. At this locality, the contact of the FQG and the adjoining retrogressed garnet bearing gneiss is occupied by a seven metre-wide basic gneiss. Stevens (1988) observed several basic gneisses near the contact.

Associated with the FQG in places are Ba-rich leucocratic calc-silicate rocks, leucocratic quartz-feldspar rocks, 'spotted quartz' rocks and thin, elongate basic gneiss bodies (Johnson and Klingner, 1976; Willis, et. al., 1983; Stevens, et. al., 1988). The association of calc-silicate rocks and the FQG is also observed in the Footwall Succession stratigraphy in the near ore position in the Pasminco Mine (see section 4.3.6). Potosi gneiss seems to grade into such calc-silicate units in this position, suggesting that the FQG, Potosi gneiss and calc-silicate horizons are genetically related.

FQG and amphibolites of the Consols Amphibolites (section 4.3.3) are also very closely associated, and in direct contact in surface exposures, for much of the strike length of the central mining field. The separation increases at depth and to the southwest. The amphibolites have a complex stratigraphic association with the ABM Potosi Type Quartzofeldspathic Gneiss as well and the entire package from FQG to the orebodies and all elements of the transition are intercalated in the near ore position in the Pasminco Mine (see section 4.3.6).

One to two planar amphibolite units are developed on the footwall of the FQG throughout the mineralised region of the mining field (within the central mining field and to the southwest). They diverge from the FQG to the northeast where a wedge of clastic metasediments is developed. Beyond the northeastern margin of the mining field (North Mine), the footwall amphibolites bifurcate into two separate belts, each consisting of a several variably lenticular amphibolite bands, and separated by a greatly thickened intermediate unit of clastic metasediments. The belts of narrow amphibolites define the hinge of the Alma Antiform (referred to by Laing et al., 1978 as the Broken Hill Synform) to the northeast of the Alma Gneiss.

The planar geometry of the FQG and its close association with units of the Consols Amphibolites and the footwall amphibolites suggests a different origin to the Hangingwall Quartzofeldspathic Gneiss (HWQG), with which the unit is correlated by workers such as Gustafson (1939); Gustafson et al., (1950); Stevens et al., (1983); Willis et al., (1983) and Haydon and McConachy, (1987). Most recently, Vassallo and Vernon,

(2000) showed that the HWQG is largely a composite intrusive body but were careful to state that their interpretation was not applicable to the FQG, which they did not examine (see section 4.5.3).

The FQG normally exhibits well-developed S1 gneissosity placing it pre-D1 (Stevens et al, 1998) and geochronological dating of the FQG in the Readymix (formerly the Australian Blue Metal or ABM) Quarry shows a magmatic crystallisation age of 1688  $\pm$  16 Ma. No younger metamorphic age was detected (Nutman and Ehlers, 1998).

The FQG (Rasp Ridge Gneiss) is interpreted to be a pile of rhyodacitic lavas and/or ash flows and the intercalated basic gneisses were either lavas or sills emplaced soon after deposition. It probably has an intrusive component as well (Stevens, et al., 1998).

### **4.3.3. Consols Amphibolite.**

The FQG has a transitional upper contact with a group of from one to four amphibolite units known as the Consols Amphibolite (Gustafson, 1939; Gustafson et al., 1950) (Figure 4.4). The Consols Amphibolite (CA) forms a well-defined belt marking the southern margin of the MinSeq throughout the Broken Hill field. The amphibolites are in contact with, or near the upper contact of the FQG throughout the centre of the mining field. However, wedges of metasediments develop to the southwest and northeast and separate the two units (Figure 4.1, in separate map folder). The upper contact of the CA is defined as the base of lowermost lens of Potosi gneiss in the overlying ABM Potosi Type Quartzofeldspathic Gneiss (see section 4.3.5).

Gustafson, (1939) recognised the CA to consist of from one to four lenticular amphibolites that reach a thickness of around 60 metres. Individual amphibolite bands are separated by units of metasediment of varying thickness. The amphibolite lenses are difficult to correlate, but were considered by Gustafson, (1939) to comprise three main belts, which he interpreted to be the result of "structural repetition". They were considered transgressive of the other formations by Gustafson, et al., (1950; 1953). To the northeast of the DeBavay Shear, the amphibolites become more structurally or stratigraphically complex (or at least appear so as a result of better exposures) and comprises several narrow bands. Near the Consols Mine, there are three separate amphibolite units with associated thinner bands. In this region, there is also an associated narrow, lenticular development of Potosi gneiss (Figure 4.1). Two of the

amphibolites are mineralised; hosting the silver-rich, structurally controlled Consols Lode (and subsidiary veins), which are late stage epithermal veins (see Chapter 5).

Browne, (1922) in Andrews (1922) described the unit as a “hornblende gabbro” containing abundant hornblende relative to feldspar and recognised that it occurred in a “bar” located just to the north of the “Alma Infants School”, probably the present day Alma Primary School. A sample collected by Browne, (1922) 200m northwest of the school consisted of mainly brownish-green hornblende and labradorite. It was well banded (“well marked by parallel structure”). In places, hornblende was so abundant relative to feldspar that the rock was called a hornblendite. This particular type of “gabbro” was only seen in the MinSeq on the footwall side of the lode and in the southwest corner of Block 14 Mine.

As well as having a close association with the FQG, elements of the CA are also closely associated with lenses of Potosi type gneiss, which lie within the CA to the immediate northeast of the ABH Consols Mine (Gustafson, 1939; see below). The amphibolite is also thicker near the southwestern extension of the ABMPG on the Pasminco southern leases, before diminishing before the Kelly’s Creek Shear is reached. ABMPG and CA thin to the southwest and down-dip to the north and northwest (see section 4.3.6).

Exceptionally iron-rich amphibolite units in the ‘underwall zone’, beneath the orebodies, are correlated with the CA and are interpreted to be metamorphosed tholeiitic volcanics. The iron enrichment is a feature that is interpreted to represent pre-metamorphic alteration (Phillips et al., 1985). However the geochemical characteristics of these rocks, including uniformly high  $\text{TiO}_2$  and  $\text{Na}_2\text{O}$ , makes their igneous origin more doubtful than for other amphibolites and mafic gneisses in the district (Phillips et al., 1985).

Higher in the Footwall Succession, in the underwall zone, narrow layers of amphibolite are interlayered with Potosi gneiss layers, BIF and magnetite-bearing pelites and locally have a magnetite-defined banding (S0 or S1). While the narrow underwall amphibolite units are not all correlated with the CA (see section 4.3.6.1), these observations suggest that at least some of the amphibolites that lie beneath the orebodies formed as calcium and iron-rich sediments.

The close association between the FQG and CA and the general geological architecture of the belt that they (and the associated lithologies) comprise is consistent with a complex mixed volcanic sequence.

#### **4.3.4. Banded Iron Formation.**

Eight separate units of quartz-garnet-magnetite rocks, known locally as banded (or bedded) iron formation (BIF) have been recognised in the MinSeq, four of which have continuity along strike (Johnson and Klingner, 1976). The narrow layers of BIF form distinctive components of the CA, in which they are most common, but are also recorded from the ABMPG (Johnson and Klingner, 1976) and in metasediments near the Potosi gneiss occurrences in the Lode Sequence (e.g. Haydon & McConachy, 1987) (see section 4.4.4). They are described here for convenience.

The majority of BIF occurrences in the MinSeq are located within the metasediments of the CA, where they comprise several narrow units (2mm to >1m) of well-layered, garnet, quartz, magnetite, apatite rocks with minor accessory biotite, ilmenite, haematite, rutile, gahnite and sulphides (Johnson and Klingner, 1976). BIF occurrences in the CA are especially focussed near the small lenses of Potosi gneiss type rocks occurring there as well as within the metasediments near the upper contact with the ABMPG. BIF bands are also associated with the contacts of the Potosi gneiss units of the ABMPG and in the Lode Sequence (see section 4.4).

The BIF-bearing metasediments and thin amphibolite bands of the upper part of the CA, and nearby units of the Footwall Succession, persist to form the underwall zone of the orebodies in the Pasminco Mine (see section 4.3.6) and in the distal MinSeq. Within the 'underwall zone', BIF layers are located within a magnetite-bearing pelite unit in the Pasminco Mine. BIF layers and the magnetite-bearing pelites associated with them are also closely associated with banded and massive magnetite-bearing amphibolite. In rare instances, bands of BIF have been observed within amphibolite bands immediately below the orebodies in the Pasminco Mine.

BIF bands are also observed in association with the Potosi gneiss occurrences on the northern contact of the main mineralised sequence in the Potosi Mine-Silver Peak Exploratory shaft area of the Pasminco Northern leases. BIF units are associated with distinctive pelite units that are known by Pasminco geologists as unit 4.8 (at the

contact with the Sundown Group) and unit 4.6. Occurrences in unit 4.6 are sporadic. A typical description of BIF within unit 4.6 is of a moderately silicified and patchily pegmatized, flesh pink banded rock with biotite speckling that strongly resembles garnet quartzite in texture and grain size. Banding is often disrupted and the unit is frequently pegmatized at contacts in this region of the MinSeq. BIF is also only weakly to non-magnetic in the region, suggesting that either there was little magnetite in the BIF, or it has been altered or destroyed post-formation.

BIF bands observed within amphibolite horizons in the Pasminco Mine 'underwall stratigraphy' and in association with variably magnetic BIF and pelites in the same horizons suggest that some degree of iron-rich chemical sedimentation took place contemporaneously with the formation of some near-ore amphibolite units. While it is also possible that BIF within amphibolite is the result of the intrusion of mafic sills along BIF horizons, the adjacent magnetite enriched metasediments and the iron enriched nature of the amphibolites (Phillips et al., 1985) suggest that the BIF could be a chemical precipitate formed contemporaneous with volcanism.

It has been suggested that two BIF horizons represent the distal "Zinc Lode" and "Lead Lode" positions (Johnson and Klingner, 1976) but this claim has not been substantiated during the present study. What is observed is that the BIF bands occupying distal positions to the main orebodies actually persist as layers in both the footwall and hangingwall of the orebodies throughout the mining field. Rather than being the distal equivalents to orebodies, they overlie and underlie the mineralisation.

#### **4.3.5. ABM Potosi Type Quartzofeldspathic Gneiss.**

The ABM Potosi Type Quartzofeldspathic Gneiss (ABMPG) is a package of lenticular Potosi gneiss units (one to four), intercalated clastic metasediments and narrow amphibolites (Figure 4.4, 4.1, 4.2 and 4.3). It forms a wide belt along the southern margin of the mining field and underlies the orebodies at depth throughout the known areas of economic mineralisation. It persists at surface as a series of readily identifiable marker units well beyond the mined zone in both the Pasminco northern and southern leases. The unit defined here incorporates the "ABM", "lower" and "middle" Potosi gneiss units defined by Johnson and Klingner (1976). The naming of this unit used here is derived from these authors and is retained because of the relationship with a key locality in the Australian Blue Metal Pty Ltd (ABM) quarry (now known as the

Readymix quarry). However, unlike Johnson and Klingner (1976), a single name is applied to the whole package of Potosi gneiss layers and their enclosing metasediments. The distribution of the main Potosi gneiss components of the ABMPG is shown in Figure 4.1, 4.2 and 4.3 (all in separate map folder). The unit bifurcates on the Pasminco southern leases, forming an upper and a lower ABMPG package.

The ABMPG package is highly variable in thickness, ranging from 450 metres to less than 10 metres and comprises multiple units of Potosi gneiss within a relatively narrow stratigraphic range that are separated by units of clastic metasediments. Southwest of the South Mine, the ABMPG consists of four separate units of Potosi gneiss, which coalesce, or thin dramatically, in the central region of the mining field. Individual Potosi gneiss units have a distinctly lenticular geometry and form an elongate; thickened 'mound'-like zone in the Footwall Succession that lies parallel to the trend of the ribbon-like orebodies. The southwestern plunge of the thickened zones is parallel to that of the orebodies and their host sequence in the Mines area (Figure 4.2, 4.3, in separate map folder). The orebodies appear to be 'draped' along the edge of the thickened part of the ABMPG package (see section 4.9).

The peripheries of Potosi gneiss units of the ABMPG are closely associated with calc-silicate-rich metasediment horizons; thin units of banded iron formation (BIF) and magnetite-bearing pelite layers. In the near-ore zone, thin Potosi gneiss units merge into amphibolite layers at their peripheries. A similar relationship is also observed with calc-silicate horizons. It is probable that all of the main Potosi gneiss units of the ABMPG merge into thin amphibolite units and/or calc-silicate horizons along their peripheries. At least two narrow, isolated bands of amphibolite occur within the metasediments separating the main Potosi gneiss units of the package. These were named the "underwall amphibolites" by Gustafson, (1939) (see section 4.3.6).

The ABMPG was first described as the "Footwall Gneiss" by Andrews, (1922) and Browne, (1922), who recognised that it occurred as lenses and persistent horizons that were generally more lenticular than either the Footwall or the Hangingwall Quartzofeldspathic Gneiss units (section 4.3.2, 4.5.3). The metasediments hosting the Potosi gneiss of the ABMPG form the footwall to the orebodies and the upper part of the Footwall Succession. Andrews, (1922) observed that the ABMPG consisted of a well-banded rock with large garnet 'eyes'; common feldspar crystals and "remarkable" convoluted pegmatite bands. The ABMPG is banded in a manner that is more

pronounced than in most phases of the Footwall and Hangingwall Quartzofeldspathic Gneiss and sillimanite is abundant at the margins in places (e.g. on ML 6 at the Zinc Corporation and on its western contact in ML's 7, 8 and 9) (Andrews, (1922).

Johnson and Klingner (1976) recognised a southwesterly "migration" of the development of the individual Potosi gneiss lenses, which has been confirmed by the present study. A fourth lens of Potosi Gneiss develops in the Pasminco Mine area, possibly as a branch of the uppermost unit (Figure 4.1, 4.2 and 4.3, all in separate map folder).

#### **4.3.5.1. *Potosi Gneiss 1 and Potosi Gneiss 2.***

Johnson & Klingner, (1976) recognised a 500m thick lowermost Potosi gneiss unit that reached its greatest thickness in a zone between the British Fault and DeBavay Shear Zone (Figure 4.1). They named this unit the "ABM Potosi gneiss", but for the purposes of this discussion, it is referred to as Potosi Gneiss 1 (PG1). A compilation of detailed surface mapping and interpretative level plans (Figure 4.1, 4.2 and 4.3, in separate map folder) reveals that there are two distinct Potosi gneiss layers represented in the thick mass of "Potosi Gneiss" described by Johnson & Klingner, (1976). A second, overlying unit is named Potosi Gneiss 2 (PG2). PG1 and PG 2 reach their greatest thickness to the northeast of the mining field where they are near merged, with only a narrow sliver of metasediments marking the separation (Figure 4.2 and 4.3, in separate map folder).

PG1 is closely associated with the overlying PG 2 and the two units are merged in the central region of the mining field. Both units reach their greatest thickness in the zone of contact, forming the large outcrops to the south of the mining field. The merged PG1 and PG2 are refolded (F4) and arched in the similar manner to the orebodies in the central mining field (see Chapter 5) and the surface expression of the merged units has been eroded away in the centre of the arch. Only the distal portions of the merged units remain, now separated into northeastern and southwestern masses (Figure 4.1).

The separation between PG1 and PG2 re-develops at depth to the northeast, in the footwall of the North Mine, where two distinct Potosi gneiss units make up the main, very thick ABMPG unit observed there (Figure 4.6). To the north of the central mining

field, PG1 and PG2 are merged into a single thin unit. To the southwest, the units separate into two distinct but approximately parallel layers (Figure 4.2 and 4.3).

#### 4.3.5.2. *Potosi Gneiss 3.*

A third Potosi gneiss unit overlies PG 1 and PG 2 and is named PG 3. It is closely associated with the footwall of the orebodies and is frequently intersected by in-mine drilling and underground development at the southwestern end of the field. Like PG 1 and PG 2, PG 3 is an elongate lens-like unit that plunges to the southwest. It thins markedly below the central mining field, bifurcating into two separate layers in the footwall of the Western Mineralisation on the South Mine 970 Level (1000 level), before fading into a marginal amphibolite unit (Figure 4.2 and 4.3, in separate map folder). PG 3 has not been recognised in the northeastern part of the mining field, seeming to wax and wane in thickness, in concert with the mineralisation.

The stratigraphic relationships of PG 3 become quite complex near the ore position in the Pasminco Mine, where it grades into calc-silicate horizons and merges with thin amphibolite bands. There is some evidence that suggests that it also splits into at least two subsidiary layers beneath the footwall of the Western Mineralisation (Figure 4.2). PG 3 is the Potosi gneiss within the 'underwall zone' of the Footwall Succession (see section 4.3.6.2).

Where there is drilling and underground mapping data available, the geometry of PG 3 has been interpreted on the geological plans included at the rear of this thesis (see especially maps NBH18, NBH19 and NBH20 in Appendix 1).

#### 4.3.5.3. *Potosi Gneiss 4.*

A fourth lens of Potosi Gneiss develops at depth between PG 2 and PG 3, in a region to the south of the Pasminco Mine (Figure 4.3, in separate map folder). It may be a branch of PG 3 but there is insufficient data to confirm this.

PG 3 and PG 4 diverge from PG 1 and PG 2 with depth to the southwest, becoming separated from the lower units by a thick wedge of clastic metasediments. The separation is fully developed by section 292, on the Pasminco southern leases (Figure 4.8).



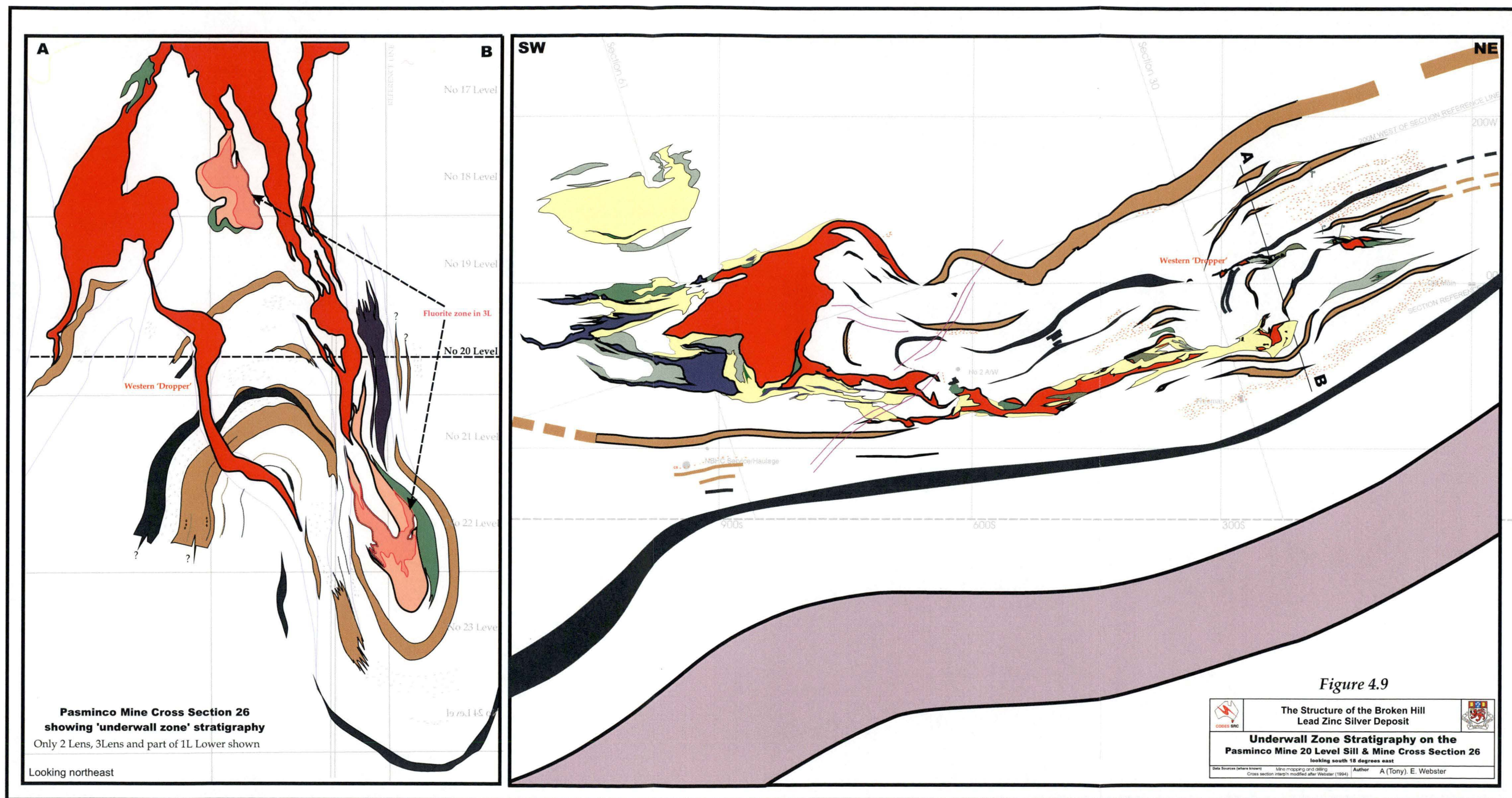
#### 4.3.6. The Underwall Zone of the Footwall Succession.

The lower part of the MinSeq has significant spatial variability and this is particularly marked in the near ore position, directly below the orebodies in the southwest part of the Pasminco Mine. In the Pasminco Mine, the entire Footwall Succession of the MinSeq, between the base of 3L and the Footwall Quartzofeldspathic Gneiss, is condensed into a 200 metres wide package, whereas in the BHP area at surface, the same sequence is 750 metres thick. The lithologies within the sequence are thinned, including all of the marker horizons and the intervening clastic metasediments, particularly those lying between the footwall of 3L and the ABMPG. The condensed Footwall Succession directly beneath the orebodies will be referred to here as the 'underwall zone' in acknowledgement of a usage by Gustafson, (1939) who identified 1 to 3 narrow amphibolite units within the zone below 3L, which he named the "underwall amphibolites". The term is used here specifically to refer to the condensed part of the Footwall Succession that lies directly beneath the orebodies and which includes the peripheral elements of the CA (thin amphibolite units and metasediments containing BIF and magnetite-bearing pelites) and the ABMPG (thin Potosi gneiss lenses, calc-silicate-rich horizons and metasediments) (Figure 4.9).

The underwall zone extends from the footwall of the lowest orebody (3L for much of the strike length of the field; 2L for some of the Pasminco Mine) or the bottom of the Lode Sequence in the Southern Cross area of the Pasminco Mine, to the upper contact of the Footwall Quartzofeldspathic Gneiss. The definition of the underwall zone is not applied to the stratigraphy beyond the mines area, though the units present within it often extend beyond the zone, as it is defined here. The underwall zone incorporates the stratigraphic positions of units previously described including the ABMPG and the CA. It also includes the positions of BIF units and the calc-silicates noted to be associated with the Footwall Quartzofeldspathic Gneiss.

While a great deal is known about the underwall zone in several key parts of the mining field, it remains the most poorly defined part of the near-ore MinSeq stratigraphy over much of the productive strike length of the field. Despite the extensive exploration and definition drilling that has been done to define the MinSeq stratigraphy in the North and Pasminco Mines, very little drilling or underground development has taken place far beyond the immediate orebody contacts. So there have been few intersections in the underwall zone for much of the central region of the





**Figure 4.9.** Detailed geological interpretations of the condensed upper part of the Footwall Succession in the 'underwall zone', Pasminco Mine, NBHC area. **4.9a** is a plan view of the 20 Level sill, NBHC area showing the interpreted distribution of the main marker horizons of the Mine Sequence. **4.9b** is a cross section interpretation of the 'underwall zone' beneath 2L and 3L in the ZC area of the Pasminco Mine (mine cross section 26). Note the fluorite-rich zone (shown in deep pink) within 3L and which defines an early layer within this orebody. For legend see the standard geological legend located in the rear map folder.



mining field. Consequently, it is the most poorly understood part of the Footwall Succession and of the mineralised environment.

Deep diamond drilling has traditionally been focussed on a series of regional sections at key intervals throughout the mining field and its distal positions. Cross-sectional interpretation of such focussed definition drilling provides most of the information about the stratigraphic environment of the orebodies (e.g. most recently Schuler et al., 1995). This drilling rarely targetted, or even intersected the immediate footwall of the orebodies, so the cross sectional interpretations of the stratigraphy tend to show blanks in the underwall zone position and to the south of the orebodies, in much of the central region. The lack of detailed information for the underwall zone for much of the length of the deposit hampers stratigraphic reinterpretations and correlation throughout the underwall zone.

The underwall zone stratigraphy is well defined at depth to the north of the central mining field (South to BHP Mines) where extensive deep diamond drilling programmes and some underground development were undertaken to explore and define the Western Mineralisation. The underwall zone was relatively well defined on the footwall of this mineralised zone as a result. The underwall zone is also relatively well known in some areas of the North Mine and on prospects on the Pasminco Northern leases. However, the best place to directly observe the zone is in the exposures that occur in the workings on the lower levels of the Pasminco Mine (17, 18, 19 and 20 Levels), where there are also an abundance of closely spaced drill hole fans that were put in as part of mine definition programmes. In this region of the field, the marker units of the underwall zone are important at an orebody scale for defining the structure of the near-ore environment and for providing stratigraphic control on mine definition and exploration drilling (Figure 4.9, maps NBH 17 to 21 in Appendix 1). It is on this southwestern part of the underwall zone that the current study has focussed.

The lack of drilling information for the greater part of the strike length of the underwall zone results in uncertainty about whether key elements of the Footwall Succession, such as the ABMPG, are present directly beneath 3L in the central mines (Figure 4.2, 4.3). This is despite the fact that they are known to occur at depth, on the footwall of the Western Mineralisation. Yet, despite the thinning of the sequence, and a paucity of drilling data in many places, all of the characteristic elements of Footwall Succession remain present in many areas and the stratigraphic elements observed in

the Pasminco Mine are observed at depth in the Pasminco northern leases and in surface outcrops.

From the available evidence, the underwall zone is characterised by the occurrence of a variety of thinly layered lithologies including Potosi gneiss (correlated with the ABMPG) and magnetic and non-magnetic amphibolites (correlated with the CA). Intercalated with the major lithologies are slivers of quartz-garnet-magnetite rock ('banded iron formation' or BIF) and horizons rich in calc-silicate bands, layers and pods (generally referred to as 'ellipsoids' at Broken Hill). The underwall zone also contains inter-banded, psammopelite, psammite and lesser pelite of clastic origin (Wright et al., 1987; Laing 1977; Laing et al., 1978; Page and Laing, 1992), with some weakly developed lode rock occurrences; mainly garnet quartzite, garnet sandstone and blue quartz-gahnite lode at the margins of 3L, 1LL and 1LU. Calc-silicate ellipsoids have been observed within Potosi gneiss and calc-silicate horizons represent along-strike equivalents of some Potosi Type Gneiss units. Potosi Type Gneiss merges into amphibolite in the underwall zone (e.g. Ransom, 1972). BIF has been observed in Potosi Type Gneiss (Figure 4.9), within and adjacent to amphibolite, and in magnetite-bearing pelite. The pelites and psammopelites that surround these units, and those that are associated with amphibolite, often contain varied amounts of disseminated magnetite. A typical drill hole intersection of the underwall stratigraphic sequence below 2L ("Lower Lead Lode") at the Pasminco Mine is presented in Appendix 5.1.

The interrelationships between the units of the Footwall Succession are changed, within the thinned underwall zone, and the sequence become more complex. For example, Potosi gneiss merges with amphibolite (Mackenzie, 1968; Ransom, 1972), grades into calc-silicate ellipsoid horizons, contains occasional calc-silicate layers, and one occurrence of BIF within Potosi gneiss has been observed (e.g. Figure 4.9) (Webster, 1994a). In the southwestern Pasminco Mine, thin amphibolite units of the CA frequently contain magnetite and are closely associated with magnetite-bearing pelite units in these locations (e.g. Figure 4.9). The close associations of these otherwise distinctive rock types in the underwall zone represent an unusual interconnectedness of the key MinSeq lithologies. The intergradations and intercalations of this thinned part of the Footwall Succession make the underwall zone the most lithologically diverse part of the MinSeq. It is of interest because, not only is it closely associated with the giant orebodies but because it shows the intimate associations of a variety of apparently distinctive lithologies that have generally been

treated as separate units and described in isolation by previous workers. These close relationships are not apparent in the distal parts of the Footwall Succession, such as the outcrops to the south of the mining field and in drilling that is distal to the main ore position. The distinction between the units of the Footwall Succession breaks down in the underwall zone, in proximity to the orebodies.

Despite the changes that are observed within the underwall zone, the condensed succession of the lower MinSeq retains a high degree of stratigraphic continuity and all distinctive horizons visible at surface to the south of the mining field persist at depth over hundreds of metres of strike extent. While the Footwall Succession becomes thinner and more compressed in the underwall zone the continuity of the distinctive lithologies within it, such as the Potosi gneiss units and amphibolites, remains and they are important for stratigraphic correlation in the Pasminco Mine. Diamond drill holes in the footwall of the orebodies were routinely stopped upon intersecting the ABMPG because they were considered to have left the potential productive part of the MinSeq.

In the northeastern part of the Pasminco Mine (NBHC and ZC Mines) the underwall zone beneath 3L consists of amphibolites (1 to 2 units), Potosi gneiss (2 units), magnetite-bearing pelite, calc-silicate-ellipsoid-bearing horizons and magnetic "BIF's. Gustafson (1939; vol 2, Table 2) mentions the "underwall amphibolites" in reference to the areas north of the Pasminco Mine and suggests that there are "one or two" and that they are probably local. He makes no mention of underwall Potosi Type Gneiss units (such as occur on NBHC 18, 19, 20 levels). No Potosi Type Gneiss has been intersected in the underwall position in the South Mine (at least in Gustafson's (1939) documentation), though they are present in the northeastern Pasminco Mine where they are exposed in development on the 17, 18 and 19 Level sills.

While the underwall zone is defined as being below 3L throughout most of the mining field, in the Pasminco Mine the clastic metasediments extend up to the base of the Garnet Quartzite Horizon (section 4.4). Therefore, the underwall zone is considered the host of the lead and calcium-rich 2L, 1LL and 1LU, as well as the quartz-fluorite-rich 3L. All orebodies hosted within the underwall zone carry significant fluorite and 2L and 3L contain abundant rhodonite. All orebodies have sharp contacts with the clastic metasediments and interdigitate with them in places (e.g. 18 Level Pasminco Mine), however there is no clastic material within the ore lenses.

The condensed package of ABMPG and CA units within the underwall zone is considered to represent the base of the main mineralising event within the MinSeq. The base of mineralisation is defined by the package of calcium-enriched rocks that includes plagioclase-rich quartzofeldspathic and garnet-rich gneiss (ABMPG), calc-silicate horizons and amphibolite (CA) interlayered with iron-enriched pelite, BIF and amphibolite. While each of the distinctive marker units within the underwall zone is mineralogically and visually distinctive, all show enrichment in calcium (Potosi-type quartzofeldspathic gneiss, calc-silicates and amphibolite) and iron (BIF, magnetite-bearing pelite and amphibolite) relative to the surrounding psammopelites and psammites. The similarity in the chemistry of the rocks in this package; their occurrence within a distinct stratigraphic position and their distinction from the surrounding metasediments suggests that they are a genetically related suite formed under special conditions that were related to the ore formation processes. Calcium-rich sediments are rare in the Willyama Supergroup and the largest single accumulation of calcium carbonate in the Broken Hill Domain is the 2L orebody. Therefore, the close stratigraphic association between 2L and this calcic package of rocks could be of genetic significance.

Variations in the underwall zone are spatially related to changes within the mineralised system, suggesting a close genetic link. The diversity of the underwall zone is greatest where it is spatially related to the maximum diversity of mineralised horizons within the mining area, particularly beneath the multiple ore lenses developed within the Lode Sequence at the southwestern end of the field. It is also marked by the thinnest sequence of clastic metasediments between the FQG and 3L (or the base of the Lode Sequence). This change in the package is possibly a stratigraphic indicator of mineralised positions.

The formation of the quartz-magnetite rocks is probably related to the process that formed the orebodies (as suggested by Andrews, 1922 and Stanton, 1972) as well as the rest of the package of calcic and iron-rich rocks that underlie them. The location of these rocks and the orebodies was not exactly concurrent in the mine area and they are separated by significant expanses of 'ordinary' psammites and psammopelites. Packages of chemical sediments with elevated calcium may be better indicators of mineralisation than the quartz-magnetite rocks contained within them. The recognition that the majority of lead and zinc within the 2L is hosted by calcium

carbonate (and is antipathetic to manganese) is further evidence for this possibility. The calcium-iron enriched units that are clustered in the footwall of 2L and 3L could be products of the processes that produced the calcium-rich components of the mineralised environment.

#### 4.3.6.1. *Underwall Amphibolites.*

The first units to be recognised in the underwall zone were two (or possibly more) thin amphibolites that were intersected by deep drill holes in the “underwall” position, within metasediments of the upper ABMPG package, beneath the orebodies in the central region (Gustafson, 1939; Gustafson et al., 1952). These intersections are still the main source of information about the zone for much of the centre of the mining field. Thin amphibolites have been intersected in the same approximate position relative to the 3L footwall and the FQG in the South, BHP and Block 14 mines (Figure 4.2, 4.3), and adjacent to the eastern contact of 3L in the upper levels of the Junction North Mine (see map NTH4, in Appendix 1). Although the details of the continuity of the amphibolite units is lacking, they are correlated with the narrow amphibolites (and associated BIF) of the underwall zone seen in the Pasminco Mine (Figures 4.9). The underwall amphibolites and BIF are closely associated in the underwall zone in the Pasminco Mine where they are also associated with magnetite-bearing pelites.

Phillips et al (1985) recognised that the amphibolites located in the footwall of the Broken Hill orebodies were exceptionally iron rich and of tholeiitic composition. They attributed the iron enrichment to post-depositional alteration.

Within the Pasminco Mine, the underwall amphibolites are texturally variable. They range from strongly banded types with a prograde gneissosity defined by amphibole abundance and bands of white plagioclase feldspar to massive or weakly banded types. The latter are usually poorly magnetic. Magnetite is often observed as discrete bands (e.g. in drill holes beneath 2L in the NBHC area of the Pasminco Mine), and where present the amphibolite is strongly magnetic. The contact regions of strongly magnetic units are usually non-magnetic. A typical magnetite-bearing example consists of dark green amphibolite with rare 1cm wide magnetite-bearing bands and has a weak banding defined by occasional feldspar and biotite. Thicker units of amphibolite may be well banded at the contacts but the intensity of the fabric may

diminish towards the centre of the unit. Other variations include finely banded varieties in which the fabric is less well defined away from contacts.

As was mentioned above (section 4.3.5), amphibolites of the underwall zone merge into a Potosi gneiss-like rock down dip and along strike in the Pasminco Mine (Mackenzie, 1968; Ransom, 1972) and in the central mines region. The underwall amphibolites described by Gustafson (1939) possibly occupy the stratigraphic position of the PG 2 of the ABMPG in the central region of the mining field.

In the upper part of the underwall zone, occasional narrow layers of amphibolite are closely associated with Potosi gneiss layers and calc-silicate horizons. One specimen collected from the 22 Sub-Level of the Pasminco Mine consists of a finely interbanded hornblende (dark green) and calc-silicate (pale grey) rock that is very reminiscent of the more commonly seen calc-silicate horizons. The fine scale banding in this specimen is hard to reconcile with the generally accepted volcanic origin for these rocks (e.g. Phillips et al., 1985). It is therefore considered likely that at least some of the amphibolites in the underwall zone, particularly those in the upper part of the Footwall Succession, formed as calcium and iron-rich sediments.

Dark coloured biotite-rich metamorphic rims, +/- some amphibole and +/- occasional amoeboid blobs of white feldspar, are often observed in amphibolites at the contact with metasediments. Coarse grained, rounded to ragged garnet is also commonly seen overprinting the contact banding. Where biotite is common, magnetite diminishes as a component of the amphibolite, suggesting retrograde metamorphic destruction. Some thin amphibolite bands have been completely altered to a black biotite, +/- garnet rock.

#### 4.3.6.2. *Underwall Potosi Type Quartzofeldspathic Gneiss.*

Potosi gneiss occurs in the underwall zone of the Footwall Succession and is correlated with the uppermost Potosi gneiss unit of the ABMPG (PG3). PG 3 lies in close association with PG 4 in the Pasminco Mine. However, it becomes separated from PG 1 and PG 2 by a thick wedge of clastic metasediments at depth, to the northeast of South Mine (Figure 4.2 and 4.3, in separate map folder). Drilling has intersected such units throughout the underwall zone of the Pasminco Mine and in the footwall of the Western Mineralisation in the central part of the field. Rare exposures in underground



workings on the Western Mineralisation are also known. Occasional intersections have shown that PG 3 is present in parts of the Central and South Mines. However, it is unlikely that it is present within the immediate underwall zone of 3L in the central region because extensive underground development has not intersected it, as it has in the Pasminco Mine. Key cross sections of the mining field, most recently re-compiled by Schuler et al., (1993), show 'blanks' in the underwall zone position to the northeast of the BHP Mine and it is poorly defined. This is also the case at depth in the North Mine, though limited underground development and drilling have intersected Potosi gneiss (probably PG 3 or 4). The available data, summarised in Figure 4.2 and 4.3, suggest that the underwall Potosi gneiss unit(s) merge into a narrow amphibolite before lensing out in the region of the Block 14/British Mines. PG 3 is therefore interpreted to be absent from the greater part of the strike length of the central and northeastern parts of the mining field.

In the Pasminco Mine, there are two to four main Potosi gneiss units in the underwall zone and they are intimately associated with amphibolite in places (Carruthers & Pratten, 1961; Mackenzie, 1968; Ransom 1972; Webster, 1993). Small bands of amphibolite lie within and adjacent to Potosi gneiss. Potosi gneiss-like bands have a similar relationship with amphibolite. Amphibolites in the underwall zone of the Pasminco Mine have been observed to grade into a Potosi gneiss-like rock (Mackenzie, 1968) that differs from more typical Potosi gneiss by being more calcic, richer in biotite and garnet and lacking in potassium feldspar (Ransom, 1972). On Pasminco Mine Section 46, magnetite-bearing pelites are apparently interbedded with Potosi gneiss (Webster, 1994a).

One of the most interesting relationships observed between Potosi gneiss units and adjacent metasediments in the underwall zone in the Pasminco Mine is that calc-silicate horizons occupy the equivalent stratigraphic positions to Potosi gneiss units. This relationship is particularly evident in the region of the 20 Level of the NBHC section of the mine (Figure 4.9) (Webster, 1994a). Calc-silicates have been observed within Potosi gneiss units in drill hole intersections in the same region of the mine. One such occurrence was intersected between 75.2-82.4 metres in DDH 7490 (Southern leases and distal to the main orebody position). It is a strongly foliated medium grained garnet-bearing Potosi gneiss-like unit with a well-developed foliation defined by bundles of fibrolite. Within the unit are four bands of greenish pink calc-silicate ranging from 8-10cm wide. As is the case with most other distinctive lithologies of the

Footwall Succession in the underwall zone, the Potosi gneiss bands grade into other rock types with which they are closely associated in the sequence.

#### 4.3.6.3. *Underwall Banded Iron Formation and Magnetite Pelite.*

In the underwall zone of the Pasminco Mine, BIF is closely associated with Potosi gneiss and thin bands of amphibolite. It has also been identified within amphibolite and thin bands have been noted in association with calc silicate ellipsoids associated with Potosi gneiss (Figure 4.9). Above all, however, BIF units in the Pasminco Mine are interlayered with a unit of magnetite bearing pelite.

The metasediments and amphibolites that are associated with BIF in the underwall zone are variable, but a typical intersection of the magnetite-bearing lithologies is seen in Diamond drill hole 7026 (full drill log in Appendix 5.1). The magnetic metasediment interval is preceded down hole (116.8-118.1m) by a strongly magnetic, finely banded amphibolite and a lower non-magnetic band. From 118.1m, there is a sequence of interbanded biotite-sillimanite rich pelite (biotite, quartz, sericite, fine & coarse-grained garnet, sillimanite and fine-grained feldspar) and psammopelite (approximately 60%/40%). The psammopelite is dark grey, tending to black, with definite but indistinctly defined coarse banding. A fine granular "pepper and salt" texture occurs throughout and is caused by 0.5-3mm, spotty to lensoidal biotite clots. Very fine garnet, and 0.5mm, lensoidal sericitised sillimanite bundles also add to this texture. At around 111.6m, the interval becomes more homogeneous in texture (less differentiation between bands), and tends more to pelite. This is a dark grey to black, very siliceous (silicified?) pelite tending to psammopelite. It has an indistinct coarse banding defined by variations in the amounts of quartz, biotite and sillimanite. A fine granular "pepper and salt" texture occurs throughout and is caused by 0.5-3mm, spotty to lensoidal biotite clots. Very fine garnet, and 0.5mm, lensoidal sericitised sillimanite bundles also add to this texture. Sillimanite is variable in its distribution and is often a major component of the more pelitic, less siliceous bands.

At 122.9m the magnetite-bearing pelite is intimately interlayered with the BIF bands. It consists of a pale grey, stripy textured, sillimanite-rich pelite (sillimanite, sericite, biotite, fine-grained garnet and quartz). Fine-grained muscovite after sillimanite is common. The actual narrow pelite interval hosting the BIF and related rocks (123.6-125.0) is a biotite, magnetite and fine-grained garnet bearing rock with several thin

magnetite, quartz, fine-grained garnet, +/-chalcopyrite bearing intervals within it. The pelite is strongly magnetic. Two narrow garnet-rich bands are transitional to garnet quartzite in appearance and are strongly magnetic. These occur at 124.3m (5cm), and 124.4m (5cm) and are probably metamorphosed BIF. A third band at 123.2m (7cm), is non magnetic. BIF bands occur at 123.86m (17cm), 124.27m (5cm), and 124.94m (13cm).

It has been suggested that the BIF horizons and the associated magnetite-bearing pelites, below the orebodies represent the position of a major D1 shear (R. C. Haydon, pers comm., 2002). The D2 'slide' of Laing et al (1978) would occupy a similar location if it were present, so could the magnetite-bearing zones beneath the orebodies be the position of the BH Antiform? Magnetite-bearing metasediments occur elsewhere in the Willyama Supergroup, such as in the Sundown Group in the 'monuments area', where they have been examined in detail by Stevens (in Stevens & Gibson, 1997) and Stevens (1999). Stevens showed that magnetite distribution was controlled by bedding and was truncated by D2 shears (equivalent to the D3A of this study) and attributed the presence of magnetite to syngenetic or syndiagenetic processes and metamorphism. The magnetite-bearing metasediments beneath the orebodies are interpreted to have originated in a similar manner, and to have formed in association with chemical sedimentation that formed the 'BIF' and the possible syndiagenetic processes that formed the magnetite precursor in the narrow magnetite-bearing amphibolites. This is discussed more fully in Chapter 5.

#### 4.3.6.4. *North Mine Underwall Zone.*

The near ore stratigraphy is poorly defined throughout most of the North Mine (CML 6), particularly the workings above the 30 Level, and is only known from drilling, especially that focussed on key cross sections such as the No 2 Shaft, Cosgroves and Imperial Ridge Sections (e.g. Schuler et al., 1993; Figure 4.6). Underground exposures are limited to mine production levels, the 21 Level, north exploration drive (map NTH21, in Appendix 1) and some access and exploratory development associated with the Fitzpatrick Orebody and focussed around the 36 Level (map NTH36 in Appendix 1). What is known about the underwall zone in North Mine is mainly derived from drill hole data and not from direct observation in underground workings. A similar situation exists in the British and Junction Mines. In the Fitzpatrick area of North Mine, exploration drilling has provided more information than is generally available

elsewhere in the northeast region of the mining field and this was partly compiled by Leyh and Hinde (1990). However, information is still relatively patchy and so only general comments can be made. More work is required.

It is apparent that the thickness of the clastic metasedimentary units of the underwall zone, especially that intercalated with the ABMPG (and lying between the 'upper' and 'middle' Potosi gneiss layers), increases relative to the main marker units. As in the southwestern part of the mining field, the latter are still markedly thinner compared with the outcrop area to the south of the field and diminish further in thickness down-dip to the north, where they are separated by a greater thickness of intervening clastic metasediments. The thickening of the underwall clastic metasediments is a feature of the central part of the mining field too and the increased proportion of these sediments as a component of the ABMPG is a persistent feature of the northeastern half of the field. It is uncertain whether the ABMPG is present within 200-250m of the footwall of 3L, despite some drilling in the area, because there is intense transposition in this region and the sparse drilling could have missed dislocated segments of the unit. The largest and most persistent unit of the ABMPG (which incorporates PG 4 and PG 3) is present at depth in North Mine but the other units lens out (possibly to amphibolite) southwest of the British Mine (Figure 4.2 and 4.3).

At greater depth below 3L, the underwall zone contains several amphibolites, and a thin Potosi gneiss unit that were intersected at depth below the Globe Vauxhall Shear Zone on No 2 Shaft section. This is more than 600m below 3L (Figure 4.6). The main mass of the ABMPG outcrops approximately 450m south of the No 2 Shaft area of North Mine, an observation that supports the view that the thickness of intervening metasediments are significantly increased in the northeast. It is unlikely that the increased thickness of the metasediments, and the apparent loss of the Potosi gneiss and amphibolites in the near ore position, is the result of structural complexity, including folding and shearing.

Other elements of the underwall zone have been observed in North Mine. Calc-silicate horizons ("epidosite eyes") were routinely mapped by mine geologists within tens of metres of the footwall contact of 3L and a single possible occurrence of amphibolite ("hornblende schist") was recorded in early mapping adjacent to 3L on the Junction Mine 4 Level (see map NTH4 in Appendix 1).

The nature of the northeastern extension of the underwall zone is unknown at depth because it is terminated against the Western Shear Zone, is structurally offset, and has not been discovered beyond the shear. Distal components of the underwall zone are well known however and have been extensively drilled on the Pasminco northern leases, at prospects such as Silver Peak and Flying Doctor. The MinSeq stratigraphy in the distal position northeast of the main orebodies is described below (see section 4.7.11).

#### 4.3.6.5. *South Mine Underwall Zone.*

In the last four decades, exploration drilling in the South Mine has been focussed on the definition of the Western & Centenary Mineralisation and this has provided a wealth of information about the stratigraphy of the MinSeq along the northern fringes of the mining area in the central region (e.g. Gentle, 1968; Haydon & McConachy, 1987). However, as in the North Mine, it provides little information about the important region directly below 2L and 3L in the main orebody position. The best information about this area is derived from surface mapping (Jaquet, 1894; Andrews, 1922; Gustafson, 1939) (Figure 4.1).

What is known from the few deeper diamond holes drilled from the lowest main levels of the South and Block 14 Mines is that between one and three thin amphibolite units are present in the Underwall Zone sequence at depth below the mines. They lie within the thickened wedge of clastic metasediments that is developed between PG3 and PG2/PG1 of the ABMPG of the Footwall Succession. The 'upper' unit of the ABMPG (PG 3) rapidly thins with depth to the north of the South Mine and eventually lenses out in the region of the footwall of the Western Mineralisation. Prior to lensing out, PG 3 merges with amphibolite (Figure 4.2 and 4.3). What is most significant about the underwall zone in these mines is that there are few recorded intersections of Potosi gneiss or BIF in the sequence, even though these lithologies should lie between the main ABMPG unit (PG 1) and 3L. "Epidosite eyes" were observed in the "upper level tunnel" of the South Mine by Andrews (1922), so calc-silicate horizons are present in this region. They are likely markers of the position of the upper Potosi gneiss units within the metasediments, but more data is required to confirm this.

In the South Mine area of the central region of the field, the distinctive marker lithologies of the underwall zone thin with depth to the northeast, probably becoming

horizons of non-distinctive rock types (or calc-silicate horizons) that were not logged in drill holes. While the marker horizons within the underwall zone pinch out or diminish, the thickness of intermediate clastic metasediments between them increases. The interval of clastic metasediments between 3L and the first occurrence of amphibolite, and that between key Potosi gneiss horizons is significantly greater than the equivalent position to the southwest; in the order of 150 metres to 250 metres, compared to around 50 metres in the Pasminco Mine. It is also possible that the sequence lies beyond the depth of drilling and only minor amphibolites associated with the top of the ABMPG have been intersected.

#### *4.3.6.6. The Transition from Underwall Zone to Lode Sequence*

The upper part of the underwall zone is transitional with the overlying mineralised sequence, except where the contact is sharply defined by the development of 3L and 2L; the two major orebodies of the deposit. These giant sulphide silicate-carbonate accumulations are intercalated with metasediments that are continuous with the upper part of the Footwall Succession and tongues of similar metasediments persist throughout the lower part of the mineralised system. It is only with the development of the calc-silicate horizons near the base of 3L and 2L and more particularly with the development of the garnet quartzite, and blue quartz rocks of the B Lode Horizon, that a truly distinctive Lode Sequence develops.

The clastic metasediments in the upper part of the underwall zone remain visually unchanged where they are intercalated with these huge accumulations of sulphides, manganese-silicates, fluorite and calcite. While occurrences of lode rocks are known on the contacts of 3L (such as the footwall garnet sandstone developed in the BHP and North Mines) and 2L, they are restricted to the orebody contacts and do not persist beyond the main sulphide bodies. The well-developed blue quartz lode on the footwall of 3L and between 2L and 3L in North Mine is the result of syn-metamorphic alteration (see Chapter 5). For most of the BH mining field, 3L and the greater part of 2L are hosted by the clastic metasediments.

## 4.4. THE LOD SEQUENCE.

### 4.4.1. Introduction

The most economically significant sulphide occurrences within the Willyama Supergroup occur in the Broken Hill area, within the Mine Sequence. These occurrences, including the main orebodies, are mainly confined within a relatively narrow stratigraphic range, in a host succession that is referred to here as the Lode Sequence (LodSeq). The LodSeq is a single package of mineralised stratigraphy within the MinSeq that hosts all of the most significant, spatially associated sulphide occurrences in the Broken Hill region (Figure 4.4).

Apart from the sulphide accumulations, the LodSeq is characterised by a suite of distinctive rock types that are characteristic of the mineralised environment and which are known by Broken Hill geologists as 'lode rocks' (see section 4.4.2). Lode rocks include 'garnet quartzite', 'garnet sandstone', blue quartz-garnet (+/- gahnite) rocks, blue quartz-bearing psammopelitic rocks and green feldspar pegmatite. Lode rocks are best developed in association with the mineralised horizons of the main Broken Hill orebodies, particularly those at the southwestern end of the mining field, in the Pasminco Mine.

In the mines area, the LodSeq is a package ranging from 50 to 250 metres in thickness. It consists of the orebodies, sub-economic sulphide occurrences, associated companion lithologies, and intervening pelitic and psammitic clastic metasediments. Sulphide occurrences have a close spatial association within the LodSeq (or its distal equivalent, known as the Lode Horizon see sections 4.4.3.2 & 4.4) and tend to occur in 'clusters', including the main orebodies, nearby mineralisation in the 4.5 Horizon (the "4.5" Mineralisation), the Western and Centenary Mineralisation, the Potosi orebody, its extensions, and the Silver Peak Extended mineralisation.

The LodSeq is best developed in association with the main orebodies in the Pasminco and South Mines where it has a well defined stratification that is capable of subdivision, as was done by Johnson and Klingner (1976) and Morland and Webster (1998). For the purposes of this study, the LodSeq consists of following units in the mines area:

- The 4.5 Horizon,
- The Upper Potosi Type Quartzofeldspathic Gneiss,
- The B Lode Horizon (mainly southwest & central regions),
- The Garnet Quartzite Horizon (southwest region only),
- 2 Lens, and
- 3 Lens.

Individual components of the LodSeq are described in detail in the following sections.

The LodSeq extends from the stratigraphic base of 3L, to the top of a narrow mineralised horizon known in the Pasmaico Mine and leases as Unit 4.5. Unit 4.5 is formally defined as being part of the Freyers Metasediments (See Figure 4.4, see also Figure 3.5 & 3.6) and is referred to in this thesis as the 4.5 Horizon (see section 4.4.3.6). Where 3L is absent, the base of the unit is the lower contact of 2L, or the base of the Garnet Quartzite or B Lode Horizons where 2L is also absent (see following sections).

A unit of Potosi gneiss, known as the Upper Potosi Type Quartzofeldspathic Gneiss (UPG), occurs within the Lode Sequence and forms a distinctive stratigraphic marker unit. This horizon has a transitional contact with the B Lode Horizon in the upper part of the LodSeq in the mines area (see section 4.4.3.5).

'Lode rocks' are also diagnostic elements of the Lode Sequence position within the Broken Hill Group on a regional basis, especially blue quartz bearing lithologies (Johnson and Klingner, 1976). In positions distal to the main orebodies, the Lode Sequence is reduced in complexity and thickness and merges with other elements of the near-ore MinSeq, including a relatively thinned package of companion lithologies and Potosi gneiss, which contains several mineralised positions. Johnson & Gow (1975), and Johnson and Klingner (1976) defined this package as the "Lode Horizon", a definition that is retained here to refer to the distal parts of the Lode Sequence beyond the main orebody position and which represents the Lode Sequence on a regional scale.



Before describing the stratigraphy of the Lode Sequence, brief descriptions of its most characteristic rock types are presented. These are the companion lithologies to mineralisation and are known as the 'lode rocks'

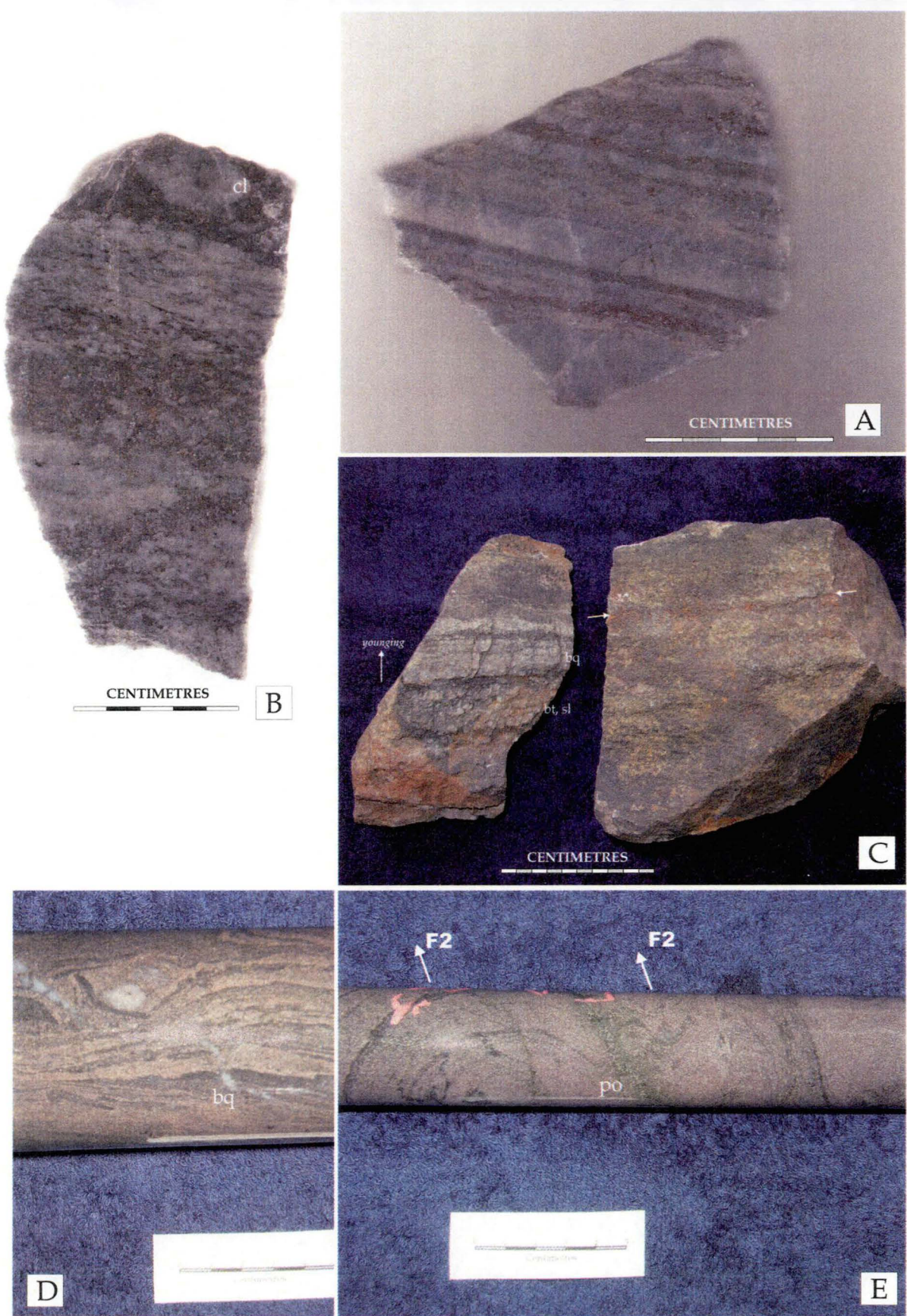
#### 4.4.2. Lode Rocks.

##### 4.4.2.1. *Introduction.*

Before discussing the stratigraphy of the LodSeq, it will be useful to describe the distinctive lithologies of the mineralised system, which are known locally as 'lode rocks', and which are the main constituents of the sequence. Lode rocks, such as garnet quartzite and blue quartz-gahnite lode, define distinct horizons within the MinSeq, which are intruded by early (syn D1?) lode pegmatite dykes. Cross bedding is observed within the laminae of garnet quartzite in many places and apparent graded bedding is seen in blue quartz bearing rocks (e.g. Figure 4.10). The early layering is deformed by D<sub>2</sub> and so was demonstrably present very early in the structural history of the deposit. Not all lode rocks are early however, and other types, such as garnet 'sandstone', formed as an alteration halo around hedenbergite-quartz veins in A Lode Lower ('Western A Lode'), within garnet quartzite, and is related to metasomatism associated with deformation processes. This evidence strongly suggests that, at least in some instances, lode rocks are an early feature of the mineralised system. This is particularly the case for garnet quartzite.

##### 4.4.2.2. *Garnet Quartzite.*

Garnet quartzite is a fine-grained, granular, massive to variably banded or laminated rock composed predominantly of spessartine garnet ( $\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ), quartz and biotite. It varies in colour from purple or deep pink to pale orange or pale pink in colour. Biotite is commonly speckled throughout the rock but is also observed as definite bands. Banding is more often defined by both garnet and biotite abundance. Where biotite is absent, garnet is the main component. The banding varies from sub-millimetre laminae, defined by a single band of very fine garnets in an otherwise quartz-rich matrix, to a coarser banding of up to 1-2 centimetres in width, defined by relative garnet abundances (Figure 4.11c). The banding and lamination is interpreted to be bedding because it is conformable with the unit contacts, is folded by F<sub>2</sub> (Figure 4.11b) and is intruded by early (syn D1?) pegmatite segregations and dykes. Cross



**Figure 4.10.** Companion lithologies (lode rocks') that are commonly found in association with mineralization at Broken Hill.

**4.10a.** Cut slab of blue quartz-altered metasediment found adjacent to 3 Lens in the North Mine (pillar mining area on 28 Level). Note the well preserved banding that is interpreted to be bedding. Sulphides (black and grey) have penetrated along bedding planes and fine-grained garnet is common in biotite rich layers (pink).

**4.10b.** Polished slab of blue quartz altered metasediments from adjacent to the footwall of B Lode, 17 Level sill, Southern Cross area of the Pasminco Mine. This rock is coarsely banded by varying percentages of sulphides, blue quartz, biotite and garnet. Pale bluish white regions are interpreted to be altered pegmatitic segregations.

**4.10c.** Two specimens of banded blue-quartz-garnet-gahnite 'lode' from outcrops in the southwestern part of the Lode Sequence. The specimen on the right of the view is from a locality on the southwestern slope of South Hill (to the north of the former Pasminco Exploration office). This outcrop is traditionally referred to as "C Lode" on the Pasminco Mine (the B Lode Horizon). It consists of a fine to medium grained granular textured rock that is rich in blue quartz, fine-grained garnet, biotite and some gahnite. The specimen is gossanous, being pock marked by 0.5-1.5mm goethitic cavities (after sulphides) and has a greenish tinge, probably as a result of a pyromorphite patina. There is also some coarsely fibrous sillimanite (D3). The specimen is banded by weakly defined variations in the amount of blue quartz and possibly (originally) sulphides. The rock tends to 'spotted psammopelite'. The banding is interpreted to be S0. The specimen on the left is from a small quarry on West Side Drive, It is an interbedded psammite to pelite unit that preserves graded bedding. The psammite bands are rich in blue quartz (bq) while the pelitic units are rich in biotite, sillimanite, +/- garnet and quartz..

**4.10d.** Finely laminated garnet quartzite in diamond drill core. The banding is defined by variations in the amount of fine garnet and quartz and is interpreted to be bedding because it is folded by F2, brecciated by D2 brittle deformation (which includes quartz-sulphide veining = bq) and is intruded by D1 pegmatite segregations.

**4.10e.** F2 folds in finely laminated garnet quartzite. Note the pyrrhotite-bearing D2 veins (po) which have developed adjacent to the fold hinge.



bedding is also widespread within the finely laminated styles and this shows a consistent 'younging' direction at local scales. However, since the 'foresets' are defined by metamorphic garnet, it is difficult to confirm this interpretation and a more systematic study is required.

Quartz, blue quartz and sulphide veining is common, usually in zones of deformation and is associated with localised silicification that is biotite destructive (Figure 4.12). Sphalerite is common in some less siliceous veins, while galena, chalcopyrite (patchy distribution) and pyrrhotite are common in more siliceous veins. Quartz veins are associated with localised hydraulic brecciation. Fine-grained late garnet overprints the banded fabric in many samples.

While most recognisable deformation in the garnet quartzite is brittle, minor sub-metre scale folding is observed and defined by the fine bands in the rock. In such tightly folded intervals, many sub-centimetre milky-blue coloured 'lode' quartz veins are associated with minor (centimetre-scale) tight to isoclinal folds (rounded hinges). The veins are most common towards the limbs. Veining is associated with significant localised hydraulic brecciation (white and blue vein quartz) and where well developed occupies more than 50% of an exposure or drill hole intersection. Biotite-rich garnet quartzite has been observed in association with fine veinlets of chalcopyrite, pyrrhotite and loellingite. It appears to be a wall rock alteration affect associated with the veining.

The contacts of garnet quartzite are generally quite sharp and the layers composed of it are well defined (e.g. Figure 4.11). However, there are also transitional zones with psammopelitic rocks in which the garnet it contains is similar in habit to garnet quartzite, but biotite is a higher proportion of the rock. Such fine-grained, garnet-rich psammopelites are transitional to garnet quartzite in texture and often contain 1-3mm wide, ragged, lenticular muscovite foliae. Garnet quartzite is also interbanded with psammopelite, particularly on the contact zone between the GQH and the BLH. Bands of variably garnet-rich and garnet-poor psammopelite are common in some transition zones.

The main contribution of the current research to the understanding of the garnet quartzite's has been to determine the distribution of the rock type on a mine scale and to examine the relationships of the units to the surrounding MinSeq stratigraphy and

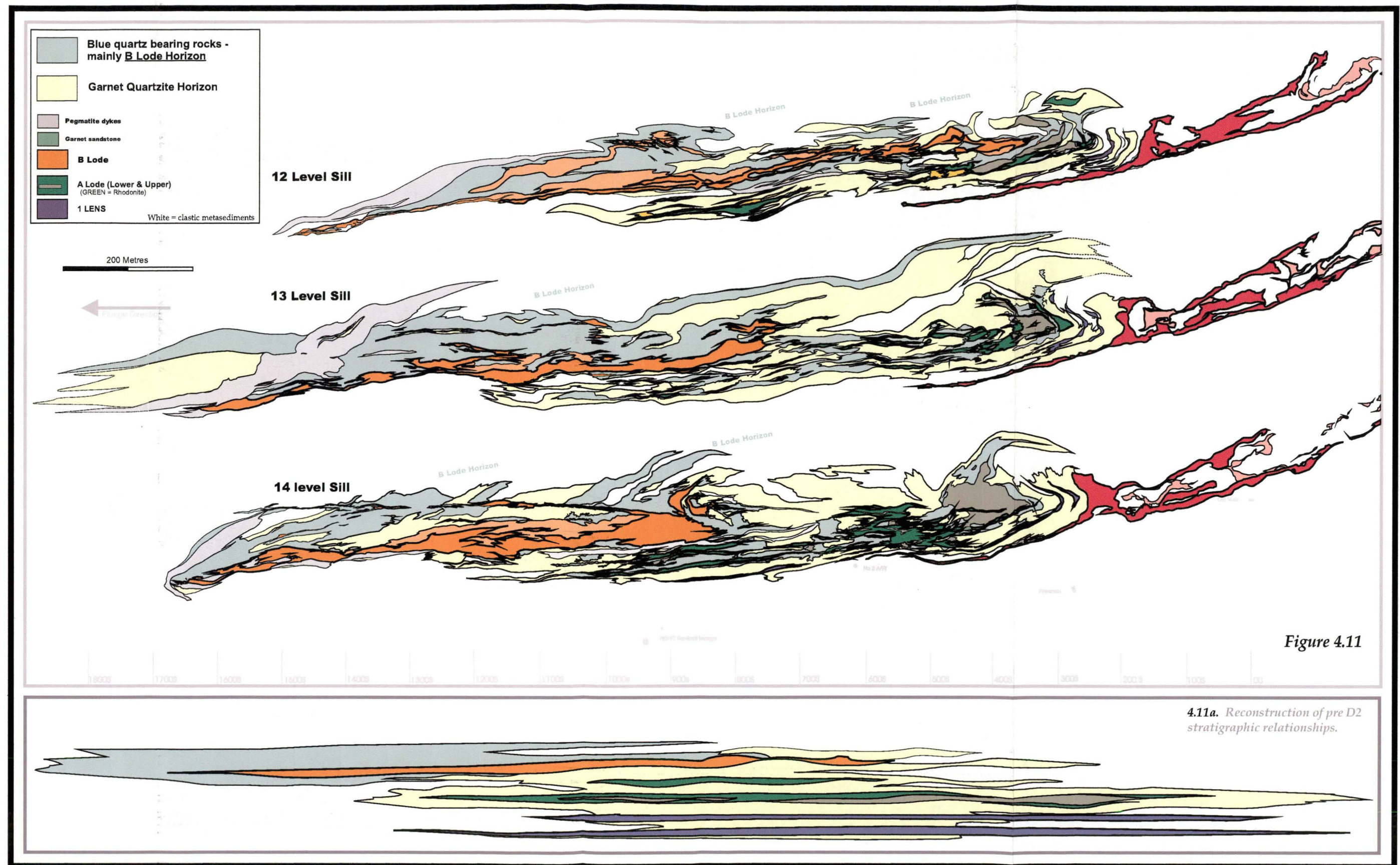


Figure 4.11

**Figure 4.11.** Stacked level plans of the Pasmaico Mine 12 to 14 Level sills showing the present stratigraphic relationships of the A Lode, B Lode and 1 Lens orebodies with the Garnet Quartzite and B Lode Horizons. **4.11a.** Schematic reconstruction of the pre-D2 relationships between A Lode Lower, A Lode Upper, B Lode & the Garnet Quartzite Horizon between the 12 & 14 Levels of the Pasmaico Mine. The B Lode Horizon is also shown. 2 Lens is shown in red and 3 Lens is shown in pink.



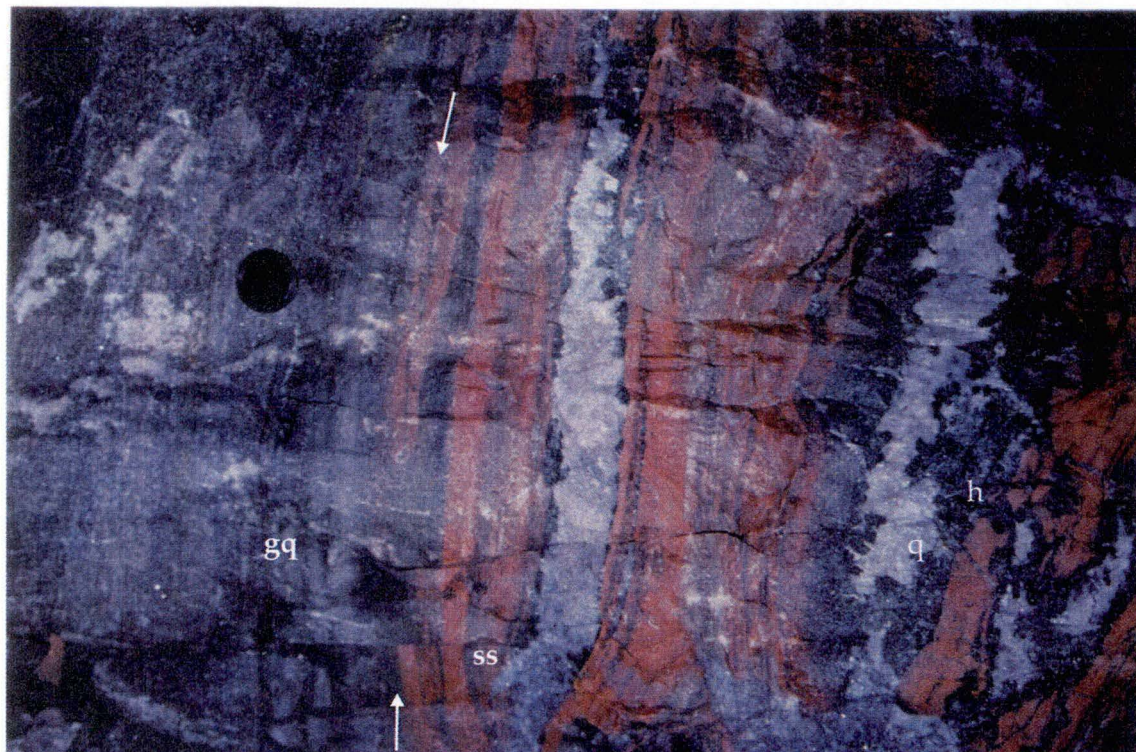
orebodies (e.g. Figure 4.11). The petrology and geochemistry of these rocks has been examined in detail by Spry (1978) who recognised at least seven different varieties of garnet quartzite based on textural and chemical characteristics. Billington (1979) undertook a detailed examination of the relationships of these rocks to the orebodies in the Pasminco Mine. The reader is referred to these works for further information.

#### 4.4.2.3. *Garnet Sandstone.*

Garnet 'sandstone' is a friable, light orange, to dark orange or pink, spessartine garnet rock composed primarily of fine to very fine-grained rounded grains of spessartine garnet. Where silicified, such as on the margins of 2L in "Area 5" of the 21 Sub-level of the Pasminco Mine, quartz fills the interstices of garnet grains and forms a matrix. Varying amounts of sulphides and white quartz veining (usually tensional, with fibrous crystal growth) are present as late phases. Sulphides, such as galena, chalcopyrite and loellingite, are minor components of garnet sandstone but occasionally reach up to 40% of some specimens, either as matrix infill or as veins. Loellingite forms well-developed crystals up to 1cm. The rock is typically strongly banded, from millimetre to centimetre scales, by variations in the garnet colour. Analyses of garnet sandstone collated by Jones (1968) showed a range of from 14.4% to 25% MnO (averaging 23%) out of 13 specimens. Webster (1993) reported that garnet sandstone had elevated levels of silver, gold (up to 1 gramme/tonne), as well as copper, arsenic and tungsten (within chalcopyrite, loellingite and scheelite respectively) in occurrences on the margins of 2L (20 Level sill; see below) and 3L (Figure 4.9a) of the Pasminco Mine.

Garnet sandstone is widespread throughout the mining field, especially as small marginal occurrences on orebody contacts (e.g. Jaquet, 1894; Jones, 1968), but shows a strong association with 3L and 1LL. Rarely, large bodies are developed, four of which are of mappable size on the mining field:

- There is a large and persistent zone located on the footwall and northwestern side of 3L in the Junction, Junction North and North Mines (refer to maps NTH2, NTH3 and NTH4 in Appendix 1). It outcrops on the north end of a cutting adjacent to the brace area of Browne Shaft (now a tourist lookout) (refer to Figure 5.16). This zone persists at depth, down to the upper levels of North Mine.



**Figure 4.12**

**4.12a.** Photograph of face in the Western A Lode 'toe' area, 17 Level, Pasminco Mine. Garnet quartzite-sandstone alteration front. Alteration to garnet sandstone is associated with the quartz-hedenbergite veins (right). The alteration front cross-cuts the banded fabric of the garnet quartzite. The banding is preserved in the garnet sandstone. Lens cap shows scale.

White arrows mark the front of alteration.

q = white quartz vein  
 h = hedenbergite  
 gq = garnet quartzite  
 ss = garnet sandstone



**4.12b.** Hand specimen of finely banded garnet quartzite that has been partially altered to garnet sandstone. The alteration front cross-cuts the original banding of the garnet quartzite and is preserved in the garnet sandstone. A pyrrhotite-rich band occupies the alteration front, within the garnet quartzite. Specimen collected by Scott Stansfield, 1997.

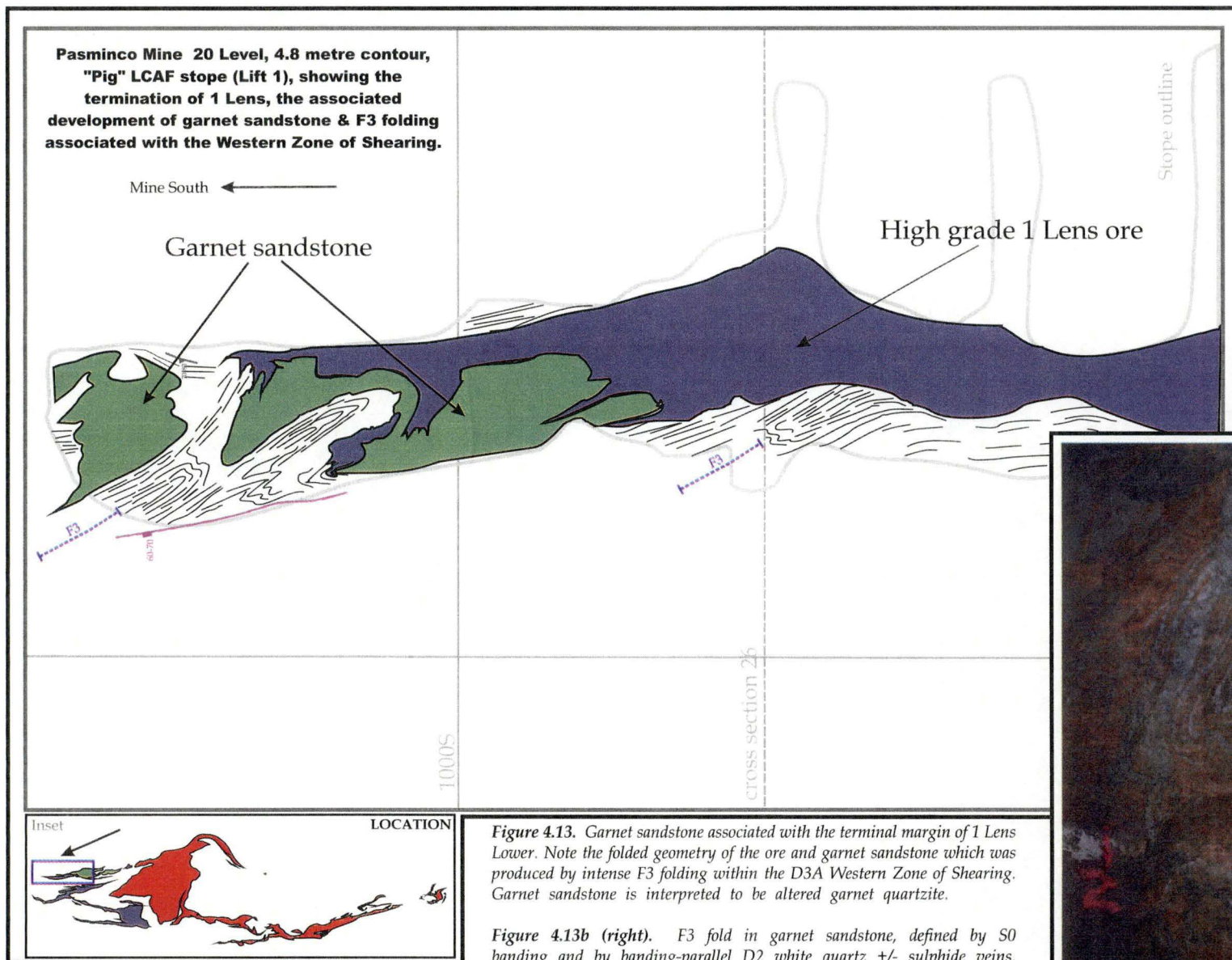


- A large mass is centred around the sill of the 20 level of the Pasminco Mine and marks the termination of 1LL on the northern side of the mineralised zone (Webster, 1994a), (Figure 4.13).
- A persistent mass is located on the southern side (footwall) of 3L in the "Southern Panel" region of the Pasminco Mine between the 21 and 23 Levels. This zone is enriched in gold and silver (Webster, 1994a), (Figure 4.9a).
- A further large zone of garnet sandstone occurs throughout the lower levels of the BHP mine on the footwall of the 3L orebody (e.g. refer to map BHP3, in Appendix 1, and also to Figure 5.17a). The garnet sandstone in this zone was a significant ore resource, containing extreme silver grades, to the point that garnet sandstone was recorded as forming a significant 'gangue' constituent of economically mineable ore (Andrews, 1922).

Other important garnet sandstone occurrences are within the alteration halo of quartz-hedenbergite-sulphide veins in the keel of the WAL Synform (see Chapter 5) between the 17 and 20 Levels of the Pasminco Mine (Pasminco unpublished data; Prendergast, 1996; Prendergast et al., 1998). A significant occurrence of garnet sandstone lies in the keel of the NBHC Synform, between the 9 and 11 Levels of the Pasminco Mine (refer to maps NBH9, 10 and 11 in Appendix 1). This garnet sandstone development lies near the northeastern termination of ALU in a structural position that is analogous to that of the garnet sandstone zone on the 17 Level. A small but persistent occurrence of garnet sandstone occurs on the footwall of (and within) 3L, on the northern limb of South Mine Antiform. This zone persists from the 625 to the 1070 Levels of the South Mine (refer to maps STH625, 725, 825, 970 and 1070 in Appendix 1).

Spry (1978) recognised that garnet sandstone was derived from garnet quartzite by loss of quartz. Prendergast (1996) argued that garnet sandstone developed on the margins of quartz-hedenbergite veins in Western A Lode, on the 17 Level of the Pasminco Mine and was formed from garnet quartzite by the addition of manganese (Figure 4.12). This process was syntectonic and took place at relatively high metamorphic grade (see Chapter 5). The alteration process that generated garnet sandstone was relatively passive. The banding of the original garnet quartzite is preserved across the alteration front and persists within the garnet sandstone (Figure 4.12).

The best documented occurrence of a large body of garnet sandstone is the extensive, gold-silver bearing zone that occurs above the upper north-western contact of 2L and which is exposed on the 20 Level sill of the Pasminco Mine (Figure 4.13). It consists of a friable, variably silicified, light orange spessartine garnet with varying amounts of



4.13b



**Figure 4.13.** Garnet sandstone associated with the terminal margin of 1 Lens Lower. Note the folded geometry of the ore and garnet sandstone which was produced by intense F3 folding within the D3A Western Zone of Shearing. Garnet sandstone is interpreted to be altered garnet quartzite.

**Figure 4.13b (right).** F3 fold in garnet sandstone, defined by S0 banding and by banding-parallel D2 white quartz +/- sulphide veins. South wall of crosscut, Panel 21, 20 Level NBHC area of the Pasminco Mine. The distance between the pink markings on the wall is 1 metre.



sulphides and white quartz veining (usually tensional, with fibrous crystal growth). The rock is typically strongly banded from millimetre to centimetre scales by variations in the garnet colour.

The 20 Level garnet sandstone body is most strongly developed between Stope sections 21-27. It is roughly lenticular in form, being structurally thickened by intense, D3A isoclinal folding and transposition that was focussed along this margin of the orebodies (Webster, 1994a, see Chapter 5). The sandstone retains some of its original layered form, despite the intensity of the deformation and was originally the termination of the branch of the Garnet Quartzite Horizon associated with the 1 Lens Lower orebody. The garnet sandstone body is anomalously rich in gold (Webster, 1993; 1994a) and gold mineralisation is best developed where the body reaches its greatest width (between Stope sections 24 and 26).

The sulphides that occur within the sandstone have textures that show that they have been introduced to it and are not an original constituent. These textures include, coarse veining, vein stockworks, sulphides as components of white quartz veins, very fine-grained matrix components and coarse grained sulphides lining the contacts with other rock types. Galena is by far the dominant sulphide, occurring as thin erratic veinlets, vein networks and as a very fine grained, steely blue matrix impregnation. Mineralised garnet quartzite has a very high specific gravity (i.e. it is heavy compared with un-mineralised sandstone).

Chalcopyrite and sometimes pyrrhotite are associated with white and clear quartz veining. Chalcopyrite and galena commonly occur as 1-4mm grains in pegmatite-like quartz veins. These veins appear to have two generations of emplacement, the first generation now occurring as indistinct, angular, translucent bluish clasts and the second forming a milky white to bluish matrix. The sulphides mostly lie on the boundary of the clasts. Veins of this type are generally parallel to sub-parallel with the banding within the sandstone but have been deformed by the D3A folding and transposition. Sphalerite is present as mostly coarser, cross cutting veins, often with associated chalcopyrite. Arsenopyrite (loellingite) is common as patches, fine 'splashes' and sometimes as coarser (sub centimetre) vein networks that cross cut the banding within the sandstone. All vein styles cross cut the sandstone banding to varying degrees, disrupting the fabric. Where sulphide veining is most strongly developed, a brecciated texture develops (Webster, 1993; 1994a).

Garnet sandstone has been altered after formation. D3A silicification (clear and saccharoidal quartz) affected the already developed garnet sandstone and garnetiferous rinds adjacent to 2L in the Belt of Attenuation in the Pasminco Mine (stope sections 24-26). A sequence from unsilicified garnet sandstone to jasperoidal silicified garnet sandstone has been mapped in the drill drives of 24-26 longhole open stope.

#### 4.4.2.4. *Blue Quartz-Garnet (Gahnite) Lode.*

Blue quartz-garnet (+/- gahnite) 'lode' is one of the characteristic rock types of the mineralised environment of the LodSeq. Blue quartz lode is a name used by Broken Hill geologists for a medium to coarse grained, milky blue to blue grey rock containing variable amounts of fine to coarse-grained greenish blue gahnite (variable retrogressed to sericite), garnet and biotite. It usually contains variable amounts of sulphides, including galena, pyrrhotite, chalcopyrite and sphalerite. The pale to light milky blue colour is often quite striking. Gahnite and garnet are not always present.

Large occurrences of blue quartz-garnet lode are found in association with most significant occurrences of mineralisation, including the main orebodies. In such localities, it is usually banded and layered and is the dominant constituent of large lenticular masses measuring tens of metres in thickness, with a strike length of many tens of metres (e.g. Round Hill and South Hill). Massive blue quartz lode also occur as haloes around vein and breccia systems in garnet quartzite (and other rock types), as stringers & bands (many centimetres thick) within spotted psammopelite and as 'rinds' on the contacts of orebodies. Many occurrences of blue quartz lode in the Potosi and Silver Peak areas of the Pasminco northern leases appear to be altered pegmatitic segregations and the margins of large pegmatite dykes are altered to blue quartz zones containing very coarse gahnite crystals in the Silver Hill area.

A large and persistent zone of blue quartz lode is located on the footwall contact of 3L throughout the North Mine. It preserves metasedimentary banding that is continuous into the adjacent metasediments. Similar contact occurrences of blue quartz lode are observed in association with B Lode in the southwestern Pasminco Mine. Blue quartz lode is often developed in both lode pegmatite and clastic metasediments adjacent to the contacts of the orebodies (Figure 4.10 a, d and a).

#### 4.4.2.5. *Spotted Psammopelite.*

Spotted psammopelite as a local name for a garnetiferous psammopelite containing common "spotty" garnets (medium to coarse-grained ragged and variably skeletal red garnets) and grading into Potosi type gneiss or quartz-rich garnet lode (Haydon and McConachy, 1987). In the mines area, spotted psammopelite is highly variable in texture and composition. It is generally dark grey to black and may contain variably developed blue quartz lode as discrete bands (possibly altered pegmatitic segregations) or as matrix. It contains variable amounts of biotite and sillimanite (hair like to horse tailed fibrolite foliae and bundles). Other variants include a 'composite' psammopelite, with many felsic bands that resemble Potosi type gneiss, and which is transitional to the psammopelite. Rounded equidimensional garnet are generally only within the bands that are rich in felsic segregations (ie: the more Potosi-like bands). In distal positions on the Pasminco southern leases, the rock type is frequently associated with calc-silicates and bands of Potosi gneiss, with which it has transitional contacts. In such localities, the Potosi gneiss grade to quartzofeldspathic psammopelite. Felsic lenses, variable biotite and sillimanite contents define an irregular gneissosity. Red garnets are very common, ranging in size from 1-2mm to 1cm (average around 3-4mm) and often have weak biotite rims. They can be ragged or augen in form. Augen garnet is most common in the more mafic zones and a later generation of fine to very fine-grained garnet is commonly speckled through the more psammitic areas. Garnets are partly altered to dark biotite to varying degrees.

#### 4.4.2.6. *Lode Pegmatites.*

Lode pegmatite is a local name for occurrences of grey and green feldspar-bearing dykes containing medium to coarse-grained K-feldspar, plagioclase and quartz with minor garnet, biotite and gahnite (in places). Two main types are recognised; irregular and patchy green feldspar-bearing intrusives within orebodies that have been dismembered to varying degrees by deformation within ore, and laterally persistent sheet-like grey feldspar, quartz and garnet bearing dykes (Johnson and Klingner, 1976). The latter are weakly transgressive of the Lode Sequence stratigraphy in the mines area and their most significant development is near the main ore bearing horizons. These rocks are discussed more fully in Chapter 5.

#### 4.4.3. Sub-Division of the Lode Sequence in the Mines Area.

There are four major sub-divisions of the Lode Sequence, if the 3L and 2L orebodies are not included (these will be discussed separately below). From south to north (mine east to mine west) they are:

- The Garnet Quartzite Horizon (southwest region of the mining field only),
- The B Lode Horizon (southwest & central regions of the mining field),
- The Upper Potosi Type Quartzofeldspathic Gneiss, and
- The 4.5 Horizon.

The subdivision of the Lode Sequence is important in a metallogenic sense as each unit hosts, or is associated with, a different style of mineralisation. The stratigraphic subdivisions of the Lode Sequence are discussed in detail below (from base to top).

##### 4.4.3.1. *The Garnet Quartzite Horizon.*

A unique unit occurs within the LodSeq in close association with the main orebodies. This distinctive unit is a well-defined, elongate, lenticular stratigraphic horizon dominated by fine-grained, pale orange-pink to mauve, banded to laminated or massive spessartine garnet-rich rock known locally as 'garnet quartzite'. It has been named the Garnet Quartzite Horizon (GQH) by Morland and Webster (1998).

Although the GQH is dominated by garnet quartzite, it also contains narrow intercalated layers of metasediments, especially along the northeastern and southwestern margins. Garnet quartzite is almost split into two separate horizons by intercalated layers of clastic metasediments below the 16 Level of the Pasminco Mine. Garnet quartzite has a sharp lateral transition to the clastic metasediments of the underwall zone at the peripheries of the GQH, particularly at the northeast and southwestern extremities (Figure 4.11). The GQH varies from less than 100 metres to 250 metres in thickness.

The lower contact of the GQH is very sharply defined while the upper contact is transitional into spotted psammopelite and variably garnet quartzite-like psammities and pelitic rocks of the B Lode Horizon (see section 4.4.3.3). Where B Lode is present,

the top of the GQH is defined as the footwall of the orebody, which occupies the base of the overlying B Lode Horizon. Fine-grained garnet-rich psammite represents the along-strike and up and down dip equivalent of the GQH, especially within the "Western Lode Limb" (Gentle, 1968). Garnet quartzite and the fine grained-garnet psammite of the Western Lode Limb can be very similar in texture, with variations in garnet percentage resulting in all gradations from psammite to 'true' garnet quartzite.

The GQH is the host horizon to the majority of smaller siliceous and zinc-rich orebodies at Broken Hill, including A Lode Upper, A Lode Lower, Southern A Lode and Southern 1 Lens and is closely associated with 1 Lens Upper and Lower, which transgress the southwestern lateral margin of the horizon. Associated with each of the ore lenses in the GQH are stratiform zones of blue-quartz-garnet (+/- gahnite) rocks, which can occupy up to 15% of the volume of the GQH. The location of the GQH reflects this close association and it is restricted in occurrence to the southwestern end of the mining field, within the Pasminco Mine, where the smaller ore lenses occur.

The zinc-rich orebodies ("zinc lodes") occur at characteristic stratigraphic levels within the GQH. A Lode Upper and A Lode Lower are the only orebodies at Broken Hill that are completely surrounded by garnet quartzite. Southern 1 Lens lies on the lower contact of the GQH, extending beyond the southwestern limits of garnet quartzite for several tens of metres.

The GQH first comes into prominence between the 5 and 6 Levels of the Pasminco Mine (ZC Area) where it has a strike length of approximately 250-300 metres. Though convoluted by folding, the GQH reaches a maximum strike length of approximately 1.5 km between the 18-19 Levels and a maximum thickness of approximately 250 metres between the 16 and 18 Levels. A thickening wedge of clastic metasediments develops between 2L and the base of the GQH down-plunge to the southwest through the Pasminco Mine. Small occurrences of GQH like zones have been observed in outcrop on South Hill, (Gustafson, 1939, Noel Carroll pers. comm., 1998) and within the Western Mineralisation (South Mine unpublished data, Haydon & McConachy, 1984) (Figure 4.1, in separate map folder).

Weak A Lode Lower-style mineralisation occurs in the Western Mineralisation, to the northeast of the Pasminco Mine, where it is defined by a narrow but distinct horizon of lenticular occurrences of garnet quartzite and mineralisation that are correlated with

the GQH (see Figures 4.2 and 4.3 or maps STH1480 and NBH6 in Appendix 1). Such zones within the Western Mineralisation are very similar to A Lode Lower in many aspects, including gangue mineralogy (rhodonite-bearing) and associated host rocks, particularly the garnet quartzite-bearing zone. A Lode Lower was probably once stratigraphically continuous with the zone in the Western Mineralisation but the 1.5 km gap between the two mineralised zones cannot be accounted for by any known structural displacement. The separation is therefore interpreted to be primary and of depositional origin, or the result of Palaeoproterozoic erosional reworking. Apart from the ALL component within the Western Mineralisation, the GQH is largely restricted to the southern half of the deposit, between the Southern Cross Shaft area and the northern boundary of the Pasminco Broken Hill Mine.

The stratigraphic position of the GQH is marked in distal locations in the LodSeq by narrow lenses and bands of garnet quartzite. These are observed in outcrop on South Hill. On a mine lease scale it is represented by variably garnet quartzite-like glassy, dark to medium grey fine-grained-garnet psammite.

The GQH is only found near the smallest of the major orebodies. Were it to have formed as an alteration associated with sulphide deposition, then it would be expected to have encompassed 2L and 3L, the two largest sulphide accumulations of the deposit. This association is not observed however, and garnet quartzite occurrences are relatively minor in association with these orebodies. 3L and 2L have sharply defined contacts with relatively unremarkable metasediments for most of their strike length. The interpretation of the garnet quartzite-dominated GQH as an alteration halo surrounding the orebodies is rejected for this reason and it is considered a type of manganese rich clastic sediment formed concurrently with the deposition of the smaller orebodies.

#### **4.4.3.2.     *The Relationship between the Underwall Zone & the GQH.***

The orebody positions within the GQH and lower LodSeq form ribbon-like units within relatively tabular stratigraphic packages; therefore, they always have a plunge component. Ribbon-shaped orebodies within enclosing stratigraphic units differ significantly in strike. This is observed in the strike of the GQH, which is several degrees more to the north than the underlying cluster of calcitic orebodies that are largely hosted within clastic metasediments (2L, 3L, 1LU, 1LL). The mineralised

positions within the GQH and the underwall stratigraphy gently diverge from the southwest to the central area of the Line of Lode. In the central areas of the field, this divergence results in a thicker expanse of intervening stratigraphy between the narrow garnet quartzite horizon in the Western Mineralisation (correlated with the GQH) and orebodies and the underwall zone amphibolites. A thickening wedge of clastic metasediments develops between the base of 2L/GQH and the CA and ABMPG positions down-plunge to the south through the Pasminco Mine.

#### **4.4.3.3. *The B Lode Horizon.***

The second unit of the Lode Sequence is a package of variably quartzofeldspathic to pelitic spotted psammopelite, quartzofeldspathic gneiss, fine-grained-garnet psammite and blue quartz-garnet-gahnite rock (which normally hosts the mineralisation) and lies above (to the north of) the GQH. It is referred to in this thesis as the B Lode Horizon, in reference to its close association with the B Lode orebody (see section 4.7.9) and the peripheral disseminated mineralisation associated with it.

The B Lode Horizon ranges in thickness from 100 to 200 metres, where best developed in the Pasminco Mine, but tapers off to less than 50 metres on the margins of the main mineralised zone. The B Lode orebody lies at the base of the B Lode Horizon, at the contact with the GQH. The upper (hangingwall) contact of B Lode is transitional with the B Lode Horizon, with the change represented by a zone of low-grade mineralisation (see section 4.7.9). In the mines area, the upper part of the B Lode Horizon is transitional with the Upper Potosi Type Quartzofeldspathic Gneiss (see section 4.4.3.5), which was interpreted by Haydon and McConachy (1987) to be the along-strike correlate of blue quartz-garnet-gahnite and spotted psammopelite of the B Lode Horizon.

The B Lode Horizon has the greatest areal extent of all LodSeq units. It reaches its greatest development in the Pasminco Mine, in association with the main orebodies but it is also extensively mineralised beyond the main BL orebody. It hosts the spotted psammopelite and disseminated blue-quartz-hosted zinc-rich mineralisation that is known as "C Lode" by mine geologists (see section 4.7.10) and it also becomes the predominant component of the LodSeq on a regional scale, defining the mineralised position throughout the Broken Hill Domain.

The northeastern extension of the B Lode Horizon forms a ribbon-like zone hosting distal B Lode style mineralisation within a distinctive stratigraphic package of rocks that is dominated by a characteristic glassy, fine-grained-garnet and blue quartz-bearing psammite known as the Western Lode Limb (Gentle, 1968). Included with the psammitic rocks are spotted psammopelite and Potosi-like quartzofeldspathic rocks, as well as some psammopelitic rocks and pelite. The Western Lode Limb psammite horizon lies to the north of 2L and 3L in the central part of the mining field and has been recognised in a region extending from the British Fault Zone (see Chapter 5) in the British-Junction region of the field to the southwest of Southern Cross Shaft in the Pasminco Mine. It represents the greater part of the Lode Sequence throughout the mine area.

The B Lode Horizon is a regionally extensive, though discontinuous and lenticular, mineralised position that hosts weak, distal B Lode-style mineralisation throughout the Pasminco Leases (including that in the Silver Peak, Flying Doctor, White Leeds and Rising Sun prospects). It forms the most significant mineralised element of the Lode Sequence to persist beyond the orebodies, where it is dominated by variably blue quartz-bearing spotted psammopelite and blue quartz-garnet (+/- gahnite) zones and contains varying proportions of disseminated sulphides. On a regional scale, the B Lode Horizon is the mineralised part of the 'Lode Horizon', as defined by Johnson and Gow (1975) (see section 4.4.4). Distal to the main orebodies, the B Lode Horizon is stratigraphically continuous with the "Lode Horizon", though the latter also incorporates the Potosi gneiss and clastic metasedimentary units from the underwall zone. The B Lode Horizon forms the greater part of the Western Lode Limb where it remakes to form the host of the Western and Centenary Mineralisation.

The B Lode Horizon occurs at depth along the northern margin of CML 7 and within ML 1249 where it hosts the mostly un-mined Western and Centenary Mineralisation (Haydon & McConachy, 1987). Evaluation drilling is currently under way (January 2003) to increase confidence in the resource estimates and definition of the Western Mineralisation for a proposed mining development (see section 4.7.9.6). The re-developed B Lode Horizon is also well developed at the Silver Peak Extended prospect on the Pasminco Northern Leases, where there is a significant occurrence of low grade mineralisation hosted in a package of rocks with many similarities to the lithologies, mineralogy and textures observed in distal regions of BL (see section 4.7.11).



B Lode and its smaller satellite lenses form ribbon-like masses of sulphide-silicate mineralisation within the blue-quartz bearing rocks of the B Lode Horizon. The B Lode Horizon in the Pasminco Mine is in turn a greatly thickened ribbon-like zone (lens-shaped in cross section) that is hosted within the tabular Lode Horizon of regional extent (see section 4.4.4). Other larger occurrences of mineralisation within the B Lode Horizon are also hosted in such elongate 'swellings', including the Western-Centenary, Silver Peak Extended, While Leads/Rising Sun and Flying Doctor Mineralisation. The mineralised package intersected in DDH 7490 on the Pasminco southern leases is another of the many other minor but significant mineralised occurrences that occur within the position of the B Lode Horizon. The B Lode style of mineralisation is recognised to be of significance on a district-scale.

#### **4.4.3.4.    *The Relationship of the B Lode Horizon and the Lode Horizon.***

Distal to the main orebodies, the LodSeq merges into a regionally significant mineralised unit named the "Lode Horizon" by Johnson and Gow (1975) and Johnson and Klingner (1976) (see section 4.4.4). The Lode Horizon is composed of components of the B Lode Horizon and the Footwall Succession, which coalesce to form a single relatively narrow stratigraphic package. The dominant contribution to the distal LodSeq (both northeast and southwest) comes from the 'B Lode'-style disseminated mineralisation and blue quartz-gahnite lode, Consols Amphibolite (underwall amphibolites), variably quartzofeldspathic psammopelite, the ABMPG, the magnetite-bearing pelite with variably developed 'BIF', variably developed calc-silicate lenses (and occasional amphibolite). The contribution to distal Lode Horizon from the GQH is negligible, consisting of occasional lenses and zones of variably garnet quartzite-like psammite and fine-grained garnet psammite. Of the main orebody positions, only B Lode is represented on a regional scale.

The B Lode Horizon and disseminated mineralisation generally referred to as 'C Lode' (mainly distal B Lode material, see section 4.7.10) are characterised by blue quartz-gahnite-garnet and spotted psammopelite lode rock types that are very similar to those that characterise the Lode Horizon (see section 4.4.4) on a district scale. In the mine, apart for the much thicker and more heavily mineralised nature of the B Lode Horizon, the rock comprising it are virtually indistinguishable from well-developed Lode Horizon occurrences elsewhere in the district. The low-grade spotted psammopelite and blue quartz lode-hosted disseminated mineralisation that is well developed at the

fringes of B Lode persists as a feature of the LodSeq to the southwest, into the Pasminco southern extensions and southern leases. In this region, beyond the main orebody position, the B Lode Horizon is stratigraphically equivalent to the main mineralised component of the Hores Gneiss (Pasminco unit 4.7) on the southern leases. Similar styles of mineralisation comprise the Western Lode Limb (see section 4.7.9.6) and that at the Silver Peak Extended and Round Hill Prospects (see section 4.7.11). The B Lode Horizon is therefore interpreted to be the predominant contributor to the LodSeq within the mines area and to be the stratigraphic link with the regionally recognised mineralised position within the Hores Gneiss that is known as the 'Lode Horizon'.

The B Lode Horizon has not yet been recognised in the 1.5 kilometre-long poorly tested zone between the northeast termination of B Lode (see Figures 4.2 and 4.3) around the 4 Level of the Pasminco Mine, and the Western Mineralisation in the central region of the mining field. Blue-quartz-garnet (+/- gahnite) lode rocks outcrop on the southwestern slope of South Hill, near the Pasminco Mine-South Mine lease boundaries and represents the last occurrences of the B Lode Horizon in this poorly tested area.

#### 4.4.3.5. *Upper Potosi Type Quartzofeldspathic Gneiss*

"Potosi Gneiss", as defined by Browne (1922), specifically referred to a narrow hangingwall belt of quartzofeldspathic gneiss that lies immediately to the north of the main orebodies, usually within 200 metres of the hangingwall. This occurrence is referred to in this thesis as the Upper Potosi Type Quartzofeldspathic Gneiss (UPG). It corresponds to the Western Series of "granulite" occurrences described by Andrews (1922). The UPG forms an important marker unit within the MinSeq on the hangingwall (northern) side of the orebodies and is particularly prominent in the region to the north and northeast of the mines area. It generally contains a single unit of Potosi type gneiss but comprises two narrow layers in the hangingwall of the Western Mineralisation on the South Mine 1000 Level (Figure. 4.2 and see map NBH6, in Appendix 1). A typical intersection of the UPG near the Potosi Mine (Pasminco DDH 3353) consisted of fine to medium grained, medium grey to bluish grey quartzofeldspathic gneiss with common 1-2mm garnets. Rare poorly defined, 1-2cm pegmatitic segregations are present throughout. In this locality, a weak retrograde schistosity defined by fine, sericite foliae is ubiquitous.

Browne (1922) described the UPG (his "Potosi Gneiss") as having a strong resemblance to finer-grained ABMPG ("Footwall Gneiss"). Within ML's 7, 8 and 9 he found it difficult to tell the difference between the UPG ("Potosi Gneiss" or "Granulite") and the associated ABMPG ("Footwall Gneiss"), noting that it appeared to simply be a "felsitic phase" of the other. Andrews (1922) observed that Potosi type gneiss, such as the UPG, always occurred close to Broken Hill type mineralisation and that in each occurrence it was intimately associated with green feldspar pegmatite.

The UPG is intimately associated with the mineralised rocks of the Lode Sequence. Unlike the ABMPG, the UPG is an integral part of the mineralised zone in the area of the main orebodies and is transitional with the spotted psammopelites of the B Lode Horizon in the central and southern parts of the mining field. There are many instances of transitional phases between this unit and the variably mineralised spotted psammopelite, Potosi gneiss-like rocks and blue quartz 'lode rocks' comprising the B Lode Horizon (e.g. Haydon and McConachy, 1987). This feature of the unit distinguishes it from all other Potosi type gneiss occurrences in the MinSeq.

Hawkins (1968) used evidence from diamond drilling within the Pasminco Mine to suggest that the UPG underwent a facies change to B Lode Horizon ("zinc lode horizon"). The UPG is consistently seen to merge with blue quartz lode rocks, variably blue quartz bearing spotted psammopelite and a variety of rock type known in the Pasminco Mine as "resembles Potosi Gneiss" ("resPG"). UPG is the stratigraphic equivalent of these rocks in positions distal to the orebody (e.g. Haydon & McConachy, 1987). The rocks do appear to have a textural and mineralogical transitional series between the end members and this is only seen in the hangingwall of the Pasminco Mine within the B Lode Horizon. The distinction is clearer in the distal Lode Sequence on the Pasminco southern and northern leases and within the Western Lode Limb (Western Mineralisation). The transitional relationship is not seen in the ABMPG. The transitional associations of the UPG with similar rock types within the main mineralised system is another characteristic that suggests that there is a clear distinction between the Potosi gneiss units of the hangingwall of the orebodies (UPG) and those in the footwall (ABMPG).

There are zones of "Potosi gneiss" that are texturally identical to the UPG within the ABMPG (Browne, 1922). UPG occurrences within the ABMPG are similar texturally,

though finer grained in hand specimen and more felsic ("felsitic") in character (Andrews, 1922). This zone forms a "bar of hard, compact gneiss that resists weathering rather better than some of the typical Footwall Gneiss" and is located on the northern side of the main ABMPG (Footwall Gneiss) outcrop on the southern (Footwall) side of the British Mine, north of the Menindee Road. However, he states very clearly that even these Potosi Gneiss-like zones within the ABMPG (Footwall Gneiss) were clearly distinct to the dominant rock type comprising the ABMPG. There are also occurrences within the UPG that are very similar to the ABMPG, particularly an occurrence in Warren St (Browne (1922). Farther northeast, the UPG develops a felsitic phase in places but weathers to form boulders similar to Footwall Gneiss (Browne (1922).

The UPG outcrops as two distinct belts due to structural repetition associated with the Hangingwall Synform (see Chapter 5). The northern belt lies to the northwest of the Globe Vauxhall Shear Zone and extends from the northern margin of the urban area (intersection of Beryl and Job Sts) to Carbonate Ridge (Figure 4.1. in separate map folder). Andrews (1922) described the northern belt as being mostly persistent but composed of discontinuous lenses. The average thickness at surface is 10 to 15 metres but it reaches its maximum width of 60 metres within the Potosi open cut mine. Browne (1922) described the petrology and chemistry of the rock type from a specimen collected at the type locality "from creek just south east of Potosi Mine" (Browne, 1922, Table of Analyses, p 324), probably Mulga Creek and which lies immediately to the north of Imperial Ridge and to the northwest of Round Hill. This locality was removed by mining of the Potosi open pit in the late 1990's.

The southern belt of the UPG occurs on the southern limb of Hangingwall Synform and has been defined, with short breaks, from the White Leads prospect on the Pasminco southern leases to Imperial Dam, adjacent to the North Mine. The main outcrop is located between the North Mine and Lords Hill. The southern belt is thinner than the northern belt; more sporadically developed at surface, and does not persist at surface for any significant distance to the southwest. Structural offsets along the Debavay Shear dislocate the southern belt to the northeast of Lords Hill. Northeast of the shear, the belt is thinned, with the last significant outcrop within the hinge of the Martins Bore Antiform (Figure 4.1 and see Chapter 5). Further to the northeast, the unit has not been found at surface to the southeast of Imperial Ridge (Figure 4.1, in separate map folder). Andrews (1922) referred to the southern belt as the "Hanging

Wall Group" and recognised that it was of a "fine texture" and closely associated with green feldspar in several localities.

The southern belt of the UPG always occurs within approximately 60 metres of the orebody hangingwall and is in contact with the orebodies in places (Andrews, 1922). In the North Mine, where this belt of the UPG is best developed at surface, it forms a relatively narrow, steeply plunging lens-like zone on the northern side of 2L and 3L. The lens-like character of the unit in this region is interpreted to be the result of D<sub>2</sub> folding and transposition. Despite discontinuities, the lens of UPG in this region is vertically persistent, extending from surface to at least the 21 Level of the North Mine (see map NTH21 in Appendix 1) where it is intersected in exploratory development. The unit has also been intersected at depth by drilling on the 36 Level (Fitzpatrick area) of the North Mine.

The UPG has been traced at depth by drilling from the Pasminco Mine and southern leases to the North Mine and beyond. It has been intersected by surface diamond drilling on the hangingwall side of the Western and Centenary Mineralisation and also by underground drilling and development on the 1470 and 1000 Levels of the South Mine (CML7 and ML 1249).

Most recent workers consider the UPG to be a structural repetition of the ABMPG (e.g. Gustafson 1939; Gustafson et al 1950; Laing et al 1978 and Haydon and McConachy, 1987). However Gustafson et al (1950) recognised the difference between UPG (Potosi) and ABMPG (Footwall) gneisses as defined by Andrews (1922) and Browne (1922) and acknowledged that "Potosi Gneiss" predominantly occurred on the western (Hanging wall side) of the lode. Gustafson et al (1950) also noted that there were fine-grained zones within the Footwall Gneiss, as mapped by Andrews (1922), which they believed could be classified as Potosi Gneiss. They went on to suggest that the "Footwall Gneiss" consisted of different phases within a single formation. It is subsequent to this observation by Gustafson et al (1950) that the differences between Potosi and Footwall Gneiss appear to have become blurred, eventually leading to the complete extinction of the term "Footwall Gneiss" when Zinc Corporation geologists abandoned the term in the 1950's.

The UPG is more closely associated with the mineralised environment than any other component of the MinSeq, with the exception of lode rocks. It is also texturally distinct

and has a distinctive outcrop habit. The Potosi type gneiss units in the hangingwall of the orebodies (UPG) are clearly different units to those in the footwall (ABMPG) and are not structural repeats of the same horizon, as was originally suggested by Andrews (1922) and Browne (1922).

#### 4.4.3.6. *The 4.5 Horizon.*

The uppermost unit of the Lode Sequence in the mines area is a widely mineralised but variably developed psammitic horizon located near the top of the Freyers Metasediments (Thackaringa Group) (Figures 4.4, 3.5 & 3.6). It consists of a variably mineralised horizon of massive blue quartz-bearing psammite, interbedded with pelites and is well bedded. The mineralised zone lies at the base of a thickly interbedded pelitic and psammitic sequence that becomes a more thinly interbanded package of pelitic, psammopelitic and psammitic layers above (Haydon and McConachy 1987). The whole package is known in the Pasminco Mine as Unit 4.5 (Haydon & McConachy, 1987; Mackenzie & Davies, 1990) but the definition applied in this thesis is restricted to the mineralised basal zone. For the purposes of this study, this basal zone is referred to as the 4.5 Horizon.

On the Pasminco northern leases, in association with the Potosi orebody, the psammite consists of a fine-grained, glassy, medium grey to dark bluish grey rock with variable proportions of interbedded pelite (massive psammite to approximately 50% pelite). Psammities are often glassy (almost translucent at times), with a dusting of very fine red garnet and occasional wispy fibrolite. Pelitic zones are typically composed of lenticular to ovoid sericite bundles (after sillimanite), biotite, minor fine-grained garnet, quartz and feldspar.

The 4.5 Horizon is separated from the UPG and other elements of the lower Lode Sequence (including a varying thickness of clastic metasediments overlying the UPG) by a laterally persistent unit of pelite that often contains a thin BIF band. The pelite contains biotite, sillimanite and feldspar, with local developments of magnetite. It is typically bedded (Haydon & McConachy, 1987). The texture of the pelites is variable throughout its known strike length. On the Pasminco northern leases, it is a light bluish-grey to dark grey rock with varying proportions of garnet. Garnet is very coarse and raggedly rounded (up to 1.5cm), to fine-grained. The garnet grains are evenly dispersed throughout the rock, or are occasionally clustered together to form

clots. Lenticular to flame shaped sillimanite bundles are usually present as either coarse clots or narrow (1-2mm) lenticular bundles. Most are retrogressed to muscovite, which may also define a retrograde foliation. Pegmatitic segregations are ubiquitous at contacts with more quartzofeldspathic layers. Magnetite is not common within the pelite on the northern leases. BIF bands are typically flesh pink in colour, layered, variably silicified and pegmatized and contain varying amounts of biotite. Some examples strongly resemble garnet quartzite.

The 4.5 Horizon has been identified throughout the mines area and adjoining leases from Kelly's Creek in the southwest to the Barrier Consolidated Mine in the northeast (Pasminco unpublished data; Schuler et al., 1993). Sub-economic zinc mineralisation is widespread within the unit, mainly contained within a massive psammite unit.

The most significant mineralised zone within the 4.5 Horizon occurs on the Pasminco northern leases where it contains the recently discovered Potosi orebody; a measured plus indicated resource of 1,041,000 tonnes at 2.3% Pb, 28 g/t Ag and 11.1% Zn (Pasminco unpublished data, 1996). This is the first economically mineable occurrence recognised within the 4.5 Horizon and it represents the second largest known accumulation of Broken Hill Type mineralisation in the Willyama Supergroup (surpassing the Pinnacles deposit which had an estimated pre-mining mined tonnage of between 600,000 and a million tonnes (e.g. Parr, 1994). The Potosi Extended and 'C' Horizon zones are strongly mineralised extensions of the Potosi orebody that are developed within 4.5 Horizon down plunge to the northeast of the Potosi open cut. They contain an indicated and inferred resource of 2.5 million tonnes grading 3.1%Pb, 40g/t Ag, 10.9% Zn and 0.3% Cu (Pasminco unpublished data, 1996). The economic mineralisation of the Potosi orebody was located between 5 and 20 metres above the stratigraphic position of the main orebodies.

A further significant occurrence of mineralisation within the 4.5 Horizon has been defined in the Pasminco Mine between sections 67 and 120, where it is referred to as the 4.5 Mineralisation. This occurrence is hosted within a variably mineralised blue quartz and garnet quartzite-bearing zone and is defined over a strike length of 1000m. It is 20-40m wide and 100m long down dip. The defined sulphide-rich occurrence lies approximately 100 to 150 metres to the north of the contact of the B Lode Horizon (Figure 4.14). Mineralisation consists of weak, disseminated to massive pyrrhotite-sphalerite-galena chalcopyrite that rarely grades in excess of 1% lead + zinc. The best-



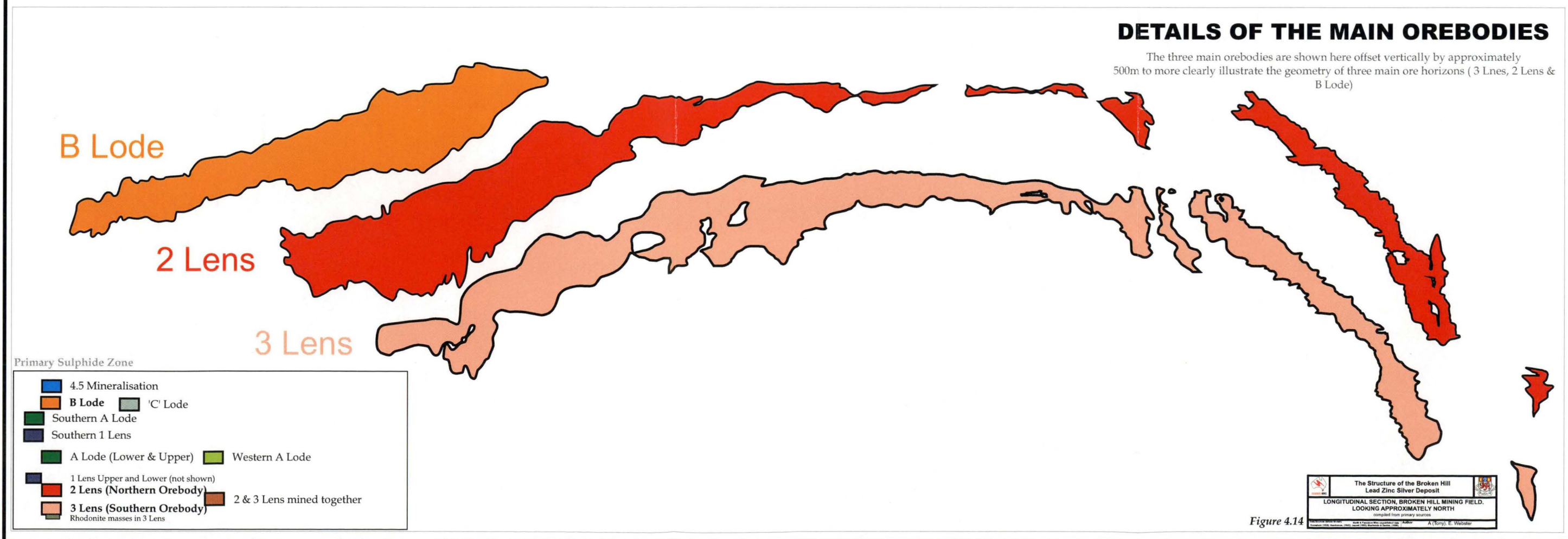
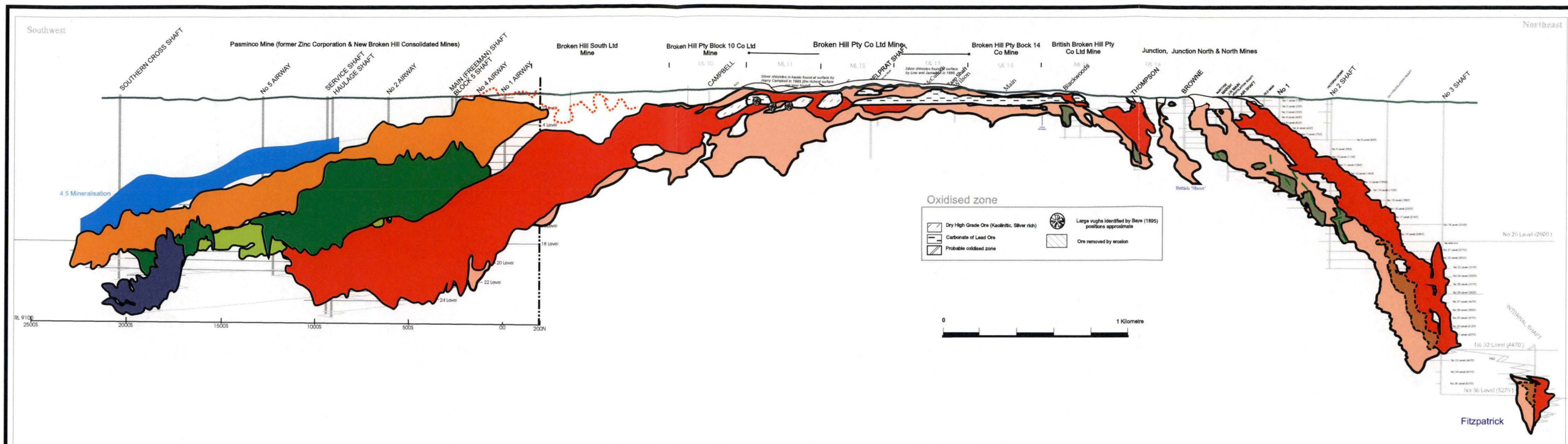


Figure 4.14



developed mineralisation recognised to date is in the top 15 metres (Mackenzie & Davies, 1990).

There are other minor occurrences of mineralisation within the 4.5 Horizon, such as the Tin Street Mineralisation (D. Larsen, pers comm, 1995). One of the most unusual mineralised occurrences within the 4.5 Horizon was intersected in DDH 7803 and 7835 on the Pasminco southern leases (cross section 340). It consisted of over a metre of massive black sphalerite associated with one of three layers of strongly banded to massive calc-silicate (probably hedenbergite). The calc-silicate was hosted within an interval of fine-grained garnet-rich psammopelite to psammite but with a five metre wide zone of extremely coarse-grained feldspar augen in the centre. Underlying the zone was a variably pelitic fine-grained garnet rich psammopelite that merged into a massive, medium grey psammite. Blue quartz was mainly present as 0.5 - 5cm wide pegmatitic segregations. This occurrence of strongly developed calc-silicates in 4.5 Horizon is the strongest encountered in the unit to date and only minor occurrences of a similar type have been observed elsewhere in the horizon. Occurrences of calc-silicates containing hedenbergite are rare in the MinSeq, outside the main ore zones, and this interesting find suggests that 2 Lens-style mineralisation occurs in other parts of the Broken Hill Group.

The package of sulphide-bearing psammites and associated rocks that comprises the 4.5 Horizon is the uppermost-mineralised occurrence in the MinSeq. Therefore, the top of this unit is taken to represent the upper boundary of the Lode Sequence for the purposes of this study. The 4.5 Horizon persists beyond the main orebody opposition and is a significant mineralised position within the Lode Horizon (see section 4.4).

#### **4.4.4. The Lode Horizon.**

The Lode Sequence diminishes in stratigraphic thickness and internal complexity away from the main Broken Hill orebodies. However, it persists for many kilometres along strike to the northeast and southwest of the mines, where it hosts the majority of minor sulphide mineralisation on a district scale. Distal to the main orebodies, the northeast, southwest, and down dip extensions of the LodSeq becomes a single horizon that incorporates elements of all LodSeq units except the GQH (compare Figures 4.5 and 4.6 with Figure 4.8). The distal extensions of the Lode Sequence are known as the Lode Horizon, following the usage of Johnson & Klingner (1976).

The LH ranges in thickness from 1 to 200 metres (Johnson & Gow, 1975) and consists of rare occurrences of 'garnet quartzite' and 'garnet sandstone' with patchy veinlets and lenses of green feldspar pegmatite, garnetiferous spotted psammopelite lenses and blue quartz-gahnite lodes of various sizes. Disseminated sulphides occasionally form narrow lenses and veins of more massive or densely disseminated material (e.g. the Flying Doctor, Silver Peak and White Leads zones, and at depth on southern leases section 292). Mineralisation is usually associated with lenses of B Lode Horizon style rocks, such as blue-quartz-garnet (+/- gahnite) and spotted psammopelite. Mineralised zones reach significant proportions in outcrop, such as on the eastern flanks of Round Hill (Figure 4.10) or on South Hill.

The distal LH is discontinuous (Johnson and Klingner, 1976) and it is not a continuously mappable unit, tending rather to occur as lenses comprising lode rocks, clastic metasediments and mineralisation. However, the position of the LodSeq relative to the surrounding MinSeq stratigraphic markers is consistently mineralised and commonly occupied by variably developed lode rocks.

Several sub-economic occurrences of Broken Hill Type sulphide occurrences lie within the MinSeq in association with well-developed Lode Horizon. Small but significant tonnages of ore were produced from the Allendale, Little Broken Hill, Rising Sun, Rupee, Silver Peak, Southern Cross and White Leads mines (for example), mainly in the late 19<sup>th</sup> Century or early 20<sup>th</sup> Century. The recently mined Potosi orebody is also hosted within the upper part of the Lode Horizon.

#### **4.4.4.1.    *The Southern Extensions and Southern Leases.***

The stratigraphic elements that comprise the underwall zone of the Footwall Succession (discussed in section 4.3.6) persist into the Pasminco Southern Leases, to the southwest of the mines, as a package of interbanded fine-grained psammite and pelite with interbedded Potosi gneiss, amphibolite and clastic metasediments. The Potosi type gneiss units of the ABMPG diminish in thickness and the amphibolites bands diminish, or merge with the Potosi gneiss units. The calc-silicate bands converge with the units of the ABMPG. Elements of the Hangingwall Succession and of the Lode Sequence (see sections 4.4 & 4.5), particularly the Upper Potosi Type

Quartzofeldspathic Gneiss, converge with the Footwall Succession to form the bulk of the distal MinSeq.

Throughout the Pasminco southern leases, the combined MinSeq package, including the Lode Horizon, represents the main orebody position. Exploration diamond drill holes DDH 7490, 7490A (shown in Figure 4.8) and DDH 7784, 7803 and 7835 (drilled in the same three month programme, on southern leases section 340) provide typical intersections of the distal MinSeq to the southwest of the main orebody position (drill log of DDH 7490 presented as Appendix 5.2). DDH 7784 intersected a 103 metre wide sequence of quartzofeldspathic gneisses (tending to Potosi type gneiss), variably developed Potosi gneiss and spotted psammopelite. Thin zones of blue quartz lode were intersected between 642.3 and 646.8 metres, at 655.8 metres and a 0.5m wide medium grade (7-10%Pb+Zn) zone was intersected at 681.7m. Most such zones were closely associated with narrow bands of spotted psammopelite. DDH 7784 was continued beyond its designed depth to test the supposed Sundown Group rocks lying stratigraphically above the Broken Hill Group. A sequence of blue quartz-rich rocks containing rare occurrences of sphalerite and pyrrhotite were intersected which more closely resemble the mineralised zones of the 4.5 Horizon (see section 4.4.3.6). This interval, lying between the Lode Sequence and the "Rasp Ridge Sequence" immediately above the Footwall Quartzofeldspathic Gneiss, represent either a continuous, weakly mineralised sequence, or a separate mineralised zone.

## 4.5. THE HANGINGWALL SUCCESSION

### 4.5.1. Town Amphibolites.

Browne (1922) recognised that a particular type of dark-coloured "garnet amphibolite", having a siliceous appearance and possessing patches of colourless to light bluish-grey quartz, and which commonly contained garnets that were visible to the naked eye, was mainly, "if not entirely", restricted to the hangingwall of the lode. He observed this rock type at Round Hill, near the Potosi Mine and within the city area. This range of observation covers the known extent of the unit, which extends from the southwestern margin of the urban area to Round Hill (Figure 4.1, in separate map folder). The cluster of up to four separate amphibolite layers was named the Town Amphibolites by Gustafson (1939) and Gustafson et al., (1950; 1953), a definition that is retained here. Clastic metasediments are interlayered with the main amphibolites in the unit.

The Town Amphibolites are exposed on both limbs of the Hangingwall Synform and the core of the Imperial Ridge Synform (see Chapter 5 and Figure 4.1). The southernmost belt is six km long; the northern belt is 2.5 km long and a third belt is defined by a major thickening in the hinge of the regional F2 Imperial Ridge Synform, in the Imperial Ridge-Round Hill region.

The Hangingwall Quartzofeldspathic Gneiss (see below) is probably partly intrusive into the Town Amphibolite horizon and it separates the thicker bands of the amphibolites on Imperial Ridge/Round Hill (shown as the "Imperial Ridge Amphibolite" in Figure 4.4) from the bands lower in the sequence (the southern belt in the urban area).

#### 4.5.2. Hangingwall Quartzofeldspathic Gneiss

The Hangingwall Quartzofeldspathic Gneiss (HWQG) defines the upper margin of the MinSeq and outcrops extensively along the northern fringes of the mining field and the BH urban area (Figure 4.1, in separate map folder). In outcrop, it comprises a 1.3 kilometre wide by 14 kilometre long lenticular and zoned body of coarse granitic gneiss.

The HWQG forms prominent hill outcrops in the city and mines area; including the Block 10 ('Joe Keenan Lookout') - Billygoat Hills at the southwestern end of Argent Street and Lords Hill, adjacent to the North Mine No 3 Shaft Infrastructure in the northeastern region. The outcrop geometry of the unit defines one of the most significant macroscopic folds in the mines area; the Hangingwall Synform (see Chapter 5). The unit outcrops more prominently than the FQG and most other units of the MinSeq.

The HWQG that outcrops on the Block 10 and Billygoat Hills is a medium to coarse-grained quartz-feldspar-biotite +/- garnet gneiss with a well-developed gneissosity. Layering is defined by scattered finer-grained quartz-feldspar-biotite lenses with less well-developed gneissosity (Stevens, 1988). More generally, it is platy in texture, with well-developed augen feldspars and elongate garnet porphyroblasts. Aplitic phases are present (Andrews, 1922; Gustafson, 1939; Carruthers & Pratten 1961). Sillimanite is present in places, particularly at the margins of the unit. The HWQG reaches its

greatest thickness at surface to the immediate northwest of Central; Block 10 and South Mines (Figure 4.1, 4.2 and 4.3, all in separate map folder). Typical intersections of the HWQG are described in Appendix 5.4.

The HWQG is generally coarsely gneissic, with well-developed augen of feldspar and elongate garnet porphyroblasts and the FQG is usually platier in appearance. Where garnet is present, the HWQG resembles Potosi gneiss (Johnson and Klingner, 1976). The HWQG is also mineralogically zoned, with the following variants mapped by the Geological Survey of NSW (Peljo et al., 2000). The codes are those used in Figure 4.1:

- BM. Medium to coarse-grained quartz-feldspar-biotite 'granite' gneiss (+/- coarse-grained augen gneiss),
- BC1. Coarse-grained augen 'granite' gneiss (Augen gneiss),
- BG2. Garnet-rich gneiss (variant 2),
- BG3/BG4. Garnet-rich 'granite' gneiss (variant 3)/sillimanite-rich 'granite' gneiss (BG3 on Broken Hill 1:25000 sheet and BG4 on Pinnacles 1:25000 map sheet, though outcrops contiguous across sheet boundaries).

The FQG and the HWQG also differ markedly in their outcrop geometry. The HWQG is a large, elongate, lenticular and mineralogically zoned mass that tapers rapidly along strike. The only recorded mineralogical zoning within the FQG is the aplitic layer observed by Andrews (1922). In comparison, in the mines area, the FQG is a relatively thin and tabular, strongly layered unit that is closely associated with the Consols Amphibolite. The HWQG is not in contact with amphibolites such as the CA.

The HWQG was distant from the mineralised position and is separated from it by the southern belts of the Town Amphibolites (see section 4.5.1) and the 4.5 Horizon (see section 4.4.4). On the other hand, the FQG is a key component of the near-ore environment in the southwestern part of the mining field, lying within 200m (Pasminco Mine) to 700m (BHP to South Mines) of the stratigraphic base of 3L through much of the southwestern and central parts of the field (e.g. Figure 4.1, 4.2, 4.3 and 4.9).

The HWQG is considered a structural repetition of the Footwall Quartzofeldspathic Gneiss by many workers (e.g. Gustafson, 1939; Gustafson et al., 1950; Laing et al., 1978; Haydon & McConachy, 1987) (see section 4.6). Consequently, the HWQG and the

FQG have both been assigned to the Rasp Ridge Gneiss of the Thackaringa Group by Stevens et al., (1983) and Willis et al., (1983). In the most recent structural interpretations (Laing et al., 1978), the correlation of the FQG and the HWQG is explained by an antiformal structure occurring between the Hangingwall Synform and the Broken Hill Synform (e.g. Laing et al., 1978). No evidence for this antiform has been encountered during the present study and the structural repetition model is not accepted here (see Chapter 5).

The textural and geometric differences between the FQG and the HWQG are considered significant enough to interpret them as separate parts of the MinSeq. Structural models that have provided mechanisms by which the FQG and the HWQG could be one unit repeated by deformation are considered inadequate (see section 4.6). Therefore, following the convention of Carruthers and Pratten (1961), the HWQG is considered a separate unit to the FQG, and is interpreted to overly the orebodies within the MinSeq. The name 'Rasp Ridge Gneiss' is rejected for the HWQG because the definition is dependent on the correlation with the FQG on the southern side of the orebody, which outcrops on "Rasp Ridge". This correlation is based on the acceptance of the structural interpretation of Laing et al (1978), which has not been supported by the current re-evaluation.

The HWQG is considered to be all or partly intrusive by Vassallo and Vernon (2000), based on field evidence; including, intrusive relationships with aplitic and leucogranite "dykes", microgranitoid enclaves and microtextural features. They argued that the HWQG is a composite intrusive body with a possible volcanic component. In their discussion, they made it clear that they were not discussing the FQG and were careful to state that their interpretations were only applicable to the HWQG and not the FQG. If the HWQG is at least partly intrusive, as seems likely from its lenticular geometry, internal mineralogical zonation and textural variations, then it may have intruded into the Town Amphibolites. This interpretation offers an explanation of why the HWQG separates the thicker amphibolites in the hinge of the Imperial Ridge Synform, on Imperial Ridge/Round Hill (the upper amphibolites; shown as the "Imperial Ridge Amphibolite" in Figure 4.4), from the more numerous, but thinner layers lower in the sequence (the southern belt in the urban area)..

#### 4.6. STRUCTURAL REPEAT OF THE MINE SEQUENCE STRATIGRAPHY.

The re-examination of the MinSeq stratigraphy undertaken as part of this study has implications for the structural interpretation of the mining field. For most of the 1960's and 1970's, the MinSeq was regarded to be a single sequence that was the right way up (e.g. Carruthers and Pratten, 1961 and Johnson and Klingner, 1976) and this interpretation has been supported by the present study. However, since the work of Laing et al., (1978), the MinSeq has been interpreted by most workers to be structurally repeated, with the Footwall Succession on the southern side of the orebodies mirror-imaged as the Hangingwall Succession on the north. The interpretation of these workers, based on new observations; including the recognition of graded bedding within MinSeq metasediments, revised the earlier model of Gustafson (1939) and Gustafson et al., (1950). The Laing et al., (1978) model requires a F2 "Broken Hill Antiform" (BH Antiform) in a position in the footwall of the orebodies to produce the fold repetition of the MinSeq.

On the scale of the mining field, the structural repeat model does not stand up to close scrutiny. The majority of significant folds that affect the Lode Sequence and which are important at orebody scale are F2 in age (Webster 1993; 1996a, this study); the same generation as is suggested for the BH Antiform. Orebody scale F2 folds show a consistent vergence to the south, suggesting that the mining field lies on the northern limb of a major regional F2 antiform. Laing et al., (1978) interpret the same folds to be F3, and to refold the F2 BH Antiform. See Chapter 5 for a full discussion.

There is no 'room' in the Underwall Zone of the Footwall Succession to accommodate the hinge of the BH Antiform beneath the orebodies. Neither has there been any evidence of a D2 "slide" occupying the F2 antiform position in the footwall rocks seen during this and previous studies (e.g. Haydon and McConachy, 1987); or during in-mine geological investigation and exploration drilling (e.g. Webster, 1993). This is despite the fact that direct observation of the zone in which it should occur is possible in underground workings. The marker units in the Underwall Zone of the Footwall Succession, such as Potosi gneiss, calc-silicate horizons, amphibolites, 'banded-iron formations' and magnetite-bearing pelites, are not repeated, truncated or attenuated, nor do they exhibit a symmetrical distribution. These units are thinner beneath the orebodies but this appears to be a depositional reduction in stratigraphic thickness and

not due to attenuation. The underwall zone is folded by F2 and dislocated by D3 shearing in the same way as the main part of the Footwall Succession.

Folds within the orebodies have been shown to be high-grade (granulite grade) and predate shearing of upper amphibolite grade (Webster 1993; 1994a; 1996a). As will be discussed in Chapter 5, the shearing pattern within the mining field does not conform to the model, or resemble the pattern suggested by Laing et al., (1978). In their model, a D2 "slide" occupies the hinge location of a postulated 'BH Antiform'. Folding of the orebodies predates the high grade shearing in the orebodies and surrounding rocks (Webster 1993; 1994a; this study) and is not D3, as Laing et al., (1978) suggest.

The structure of the gneisses surrounding the orebodies is revealed by the form surface map of the outcrop area of the orebodies (Figures 4.1, see also more detailed excerpt presented as Figure 5.1). There is no evidence of a major F2 fold hinge, such as the BH Antiform, between the FQG and 3L. The asymmetry of the minor orebody-scale F2 folds is clearly visible, as is the pattern of the D3 high-grade shears and the geometry and style of these structures is the same as those that are visible in maps of the underground workings. The surface exposure reflects the structure of the MinSeq at depth.

There is no evidence for the interpretation that the "Rasp Ridge Lode Horizon" is a structural repeat of the Lode Sequence, as was suggested by Laing et al., (1978); an interpretation borne out by observations made in DDH 7490 (Figure 4.8). These drill holes passed through the majority of the MinSeq, from the HWQG to the "Rasp Ridge Lode Horizon" sequence. No major 'slide' or F2 fold was encountered (see Appendix 5.2 for drill log). The "Rasp Ridge Lode Horizon" is interpreted here to be a separate mineralised horizon to the Lode Sequence.

As the preceding discussion has shown, there are significant textural and mineralogical differences between key marker units in the Hangingwall Succession and the Footwall Succession that are correlated by Laing et al., (1978) and Haydon & McConachy (1987). The lithological associations also vary, with the FQG being associated with several large layers of amphibolite; which the HWQG is not, and the Upper Potosi Type Quartzofeldspathic Gneiss merges with mineralised rocks of the B Lode Horizon, which the ABMPG does not. The Footwall Succession and the Hangingwall Mine Succession are not the same structurally repeated series of units



that have been refolded around a major F2 antiform; the BH Antiform. The MinSeq is a single sequence from the Footwall Quartzofeldspathic Gneiss to the Hangingwall Quartzofeldspathic Gneiss as was suggested by Carruthers and Pratten (1961).

#### 4.7. THE OREBODIES.

The Broken Hill lead-zinc-silver deposit consists of at least nine spatially associated, flattened and ribbon-like stratiform orebodies within a sequence of distinctive companion lithologies. They are contained within the Lode Sequence and have complex geometries because of multiple deformations. At the southwestern end of the field, mainly in the Pasminco Mine, there is a stacking of ore lenses within the Lode Sequence that is often described as being in an 'en echelon manner' (e.g Mackenzie and Davies, 1990) (Figure 4.15).

The lowest and second lowest orebodies in the deposit are 3 Lens and 2 Lens respectively. They have historically been the predominant ore sources at Broken Hill. They extend for most of the length of the field, a distance of over 8.5 km. In recent decades, as 3L and 2L have become depleted, several other mineralised horizons, located mainly within the Pasminco Mine at the southwestern end of the mining field, have become significant ore sources. B Lode lies at the top of the orebody succession throughout the Pasminco Mine (Figure 4.16). The lesser-mineralised horizons now account for most of the production of the field. From the lowest to uppermost, they are known as;

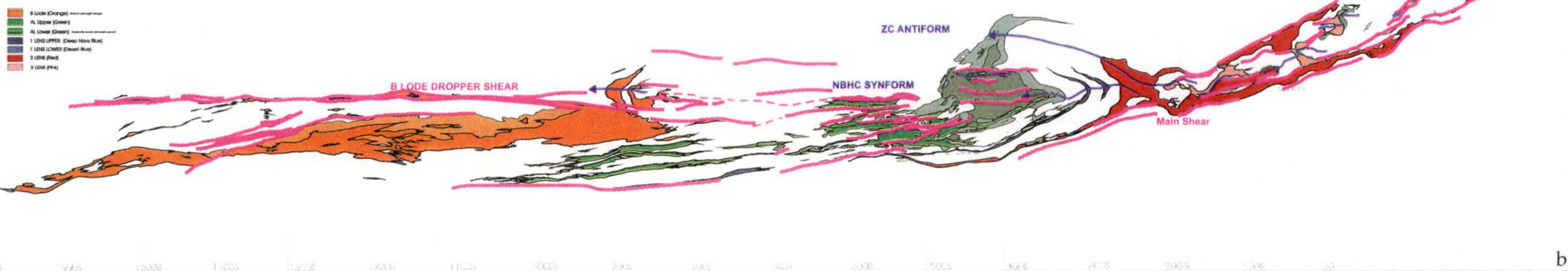
- 1 Lens Lower (1LL) immediately above 2L,
- 1 Lens Upper (1LU),
- Southern 1 Lens (S1L), a separate ore horizon occupying the 1L stratigraphic position in the southwestern part of the Pasminco Mine. Probably more closely akin to B Lode,
- A Lode Lower (ALL),
- A Lode Upper (ALU),
- Southern A Lode (SAL), in the same stratigraphic position relative to BL as ALU but is a distinct occurrence to the southwest, and
- B Lode (BL).

**Distribution of main orebodies, Pasminco Mine  
14 level Sill  
High Grade mineralised rocks, classified by orebody**



**Distribution of main orebodies, Pasminco Mine  
14 level Sill**

**STRUCTURE**



**Figure 4.15.** Distribution of the main orebodies on the 14 Level sill of the Pasminco Mine. Only high grade mineralised rocks are shown and are classified by orebody. The 14 level area of this mine preserves the primary layered distribution of the lesser orebodies better than anywhere else on the field. 4.14b shows the locations of the main F2 fold axial traces and D3A shears on this level.

Additional complexity is probably present within the broadly defined mineralised horizons. Southern 1 Lens probably consists of three separate lenses (A. Morley and J. Murray pers. comm. 2000). ALL consists of three separate distinctive mineralised horizons in the 'Western A Lode' section (Hudson, 1994). B Lode contains separate satellite lenses that are closely associated with the main mass of the orebody. Subordinate lenses and branches of the main sulphide horizons are present but further work is required to resolve these in detail.

A tenth body of economically significant, structurally mobilised and disseminated stratiform mineralisation is defined within the Pasminco Mine). It lies above BL and is known as 'C Lode' (Mackenzie and Davies, 1990; Stockfeld, 1993c). Extensive diamond drilling in the 1990's defined economically mineable areas within this body and showed that it was composed of both relatively weak stratiform and higher grade but narrow structurally mobilised mineralisation (Stockfeld, 1993c). 'C Lode' is no longer considered a separate stratiform zone of mineralisation, but consists mainly of BL mineralisation and is no longer classified as a separate orebody (see below).

*Figure 4.16. Stratigraphic order of the Broken Hill orebodies. Previous workers such as Laing et al., (1978) and Haydon & McConachy (1987) have interpreted the mines area to be overturned. No evidence for this interpretation has been recognised during this study.*

Orebody Name	Southwest Pasminco Mine	Position within Lode Sequence
'C Lode'		Not a separate ore horizon (shear hosted & distal stratiform BL)
B Lode ( <i>plus satellite lenses</i> )		Bottom of B Lode Horizon
	Southern A Lode	GQH
	Southern 1 Lens	GQH bottom
A Lode Upper		GQH
A Lode Lower ( <i>&amp; Western A Lode</i> )		GQH
1 Lens Upper		GQH (southwest end only)
1 Lens Lower		GQH (southwest end only)
2 Lens (SW)		Minor GQH rocks associated with 1L are in contact with 2L.
3 Lens		Minor GQH rocks & garnet sandstone common on footwall throughout field. Less well-developed in SW compared to NE. No contact with main GQH)

The orebodies are visually and geologically distinctive units and generally possess sharply defined contacts, which separate them from the 'lode rocks' and other wall rocks. Defining the economically important orebodies by grade cut-off definitions is

only important in ALL and ALU where syntectonic mobilisation of sulphides was extensive during D2/D3A. Although there are numerous local discordances, and mobilisation and structural modifications are widespread, each orebody shows a consistent, conformable relationship with the surrounding strata and occurs in a characteristic stratigraphic position within the LodSeq.

As discussed above, significant mineralisation occurs beyond the main orebodies, especially within the 4.5 Horizon, distal B Lode Horizon and in the regionally extensive Lode Horizon. Much of the economically significant mineralisation is spatially associated with the main orebodies (e.g. the 4.5 Mineralisation) or occurs as clusters of narrow horizons spatially focussed in the same part of the LodSeq (e.g. Potosi - Silver Peak Extended mineralisation). Distal BL-style mineralisation, with minor occurrences of ALL-style rocks (garnet quartzite and occasional rhodonite gangue in sulphides), develops in the lenticular remakes of the B Lode Horizon that occur throughout the LodSeq. The re-developments of significant zones of sulphide mineralisation within this stratigraphic position within are the next most extensive mineralised position in the region of the mining field, after 2L and 3L. Occurrences are known over a 20 kilometres strike length. The mineralisation is not stratigraphically continuous. However, all of the significant mineralisation that persists in the B Lode Horizon position within the LodSeq lies at the same stratigraphic position, which, in the mining field, was known as the "Western Lode Limb" by (Gentle, 1968).

3L is stratigraphically continuous for a strike length of 8.5 kilometres. 2 Lens has a similar strike length but is discontinuous because of structural dismemberment. B Lode and the low-grade mineralisation within the B Lode Horizon is the next most extensive mineralised position in the field, persisting for 5 kilometres. The orebodies are arranged in an en echelon manner from north east to south west, with 3L the predominant orebody at the north end of the field. The en echelon arrangement is most pronounced at the southern end of the field where the greatest number of lenses occurs.

Massive sulphides form only a minor part of each orebody and are most common in deformed regions of the lenses. Sulphide-rich mineralisation is more often coarsely banded, with banding defined by variations in gangue mineral and sulphide abundances (Webster, 1993; 1994a; 1996a). Each orebody is composed of a high percentage of gangue minerals including primary calcite, fluorite, apatite, calcic or

manganese pyroxenoids/pyroxenes or quartz that are distributed through the mineralisation as discrete bands, layers and 'stratigraphic' horizons. Sphalerite (marmatite) is the dominant sulphide constituent of all ore lenses. The percentage of galena progressively diminishes in each orebody from 3L to BL. Important accessory sulphides include pyrrhotite, chalcopyrite and loellingite. Galena distribution is frequently heavily influenced by D2/D3A folding and transposition and defines an S2 fabric in the northeastern parts of the deposit (see Chapter 5).

The stratigraphy of the near ore LodSeq, and much of the early gangue and sulphide-defined banding (S0) of the orebodies and near-ore rocks, is conformable. The best lines of evidence for the pre-folding, conformable nature of the orebodies are:

- B Lode Horizon stratigraphy that develops as a transition zone on the hangingwall of the main BL sulphide body,
- The GQ Horizon and its sharp contacts with several "zinc lodes" and their positions within it,
- The interdigitation of 2L, the rhodonite zone, and surrounding metasediments in the Pasminco Mine below the 17 level, and its 'mother-daughter' relationship with 1LL and 1LU,
- The apparent 2L-like zones that are developed in 3L in this same region, and
- The cross-cutting relationship of D<sub>1</sub> lode pegmatite's to the stratigraphy and structure of the orebodies and Lode Sequence.

All of these relationships are discussed in detail below.

#### **4.7.1. Early Layered Features of the Orebodies (S0).**

The Broken Hill orebodies preserve an early stratification (S0). Most major bodies contain variations in gangue and sulphide densities that define layers and banding which pre-date the earliest phase of pegmatite intrusion (syn D1?) and folding (D2). Such variations are manifested as banding, stratiform gangue mineral distribution, sulphide-depleted layers and sulphide-enriched layers. Banding and layering is usually sub-parallel to nearby orebody contacts (Webster, 1993; 1994a).

The extremities of the orebodies also show variations that are attributed to early stratigraphic interrelationships with wall rocks. Peripheral regions of some orebodies,

such as 2L and 3L, undergo progressive changes in mineralogy, such as the development of pyrrhotite-rich margins in 2 Lens and a 2 Lens-like zone in 3 Lens, and the layering in the margins closely interdigitate with metasedimentary wall rocks and 'lode' rocks. Such features will be described in more detail in the following sections. There is a close relationship between the stratigraphy of the orebodies and the surrounding Mine Sequence (MinSeq) stratigraphy. The orebodies and Lode Sequence are not 'foreign' introductions into the MinSeq but are an integral part of it.

The layering/banding of the orebodies and Lode Sequence that are considered to be primary (S0) features are summarised in Figure 4.17.

#### **4.7.2. Orebody Geometry.**

All Broken Hill ore lenses and associated mineralisation are strongly elongate ovoids. The ovoids lie parallel to stratigraphy, with long axes approximately parallel in strike and roughly lenticular in cross section. The extreme along-strike length of 2L, 3L, ALL, distal B Lode style mineralisation and the mineralisation within the 4.5 Horizon produces a series of "ribbons" of mineralisation, the most consistent of which are 2L and 3L. The elongation of the ore lenses is a characteristic of orebodies in the BH region.

Orebodies and associated 'lode rocks' form ribbons within the otherwise tabular stratigraphic units of the LodSeq (Figure 4.14). This is an important observation, because the present ribbon-like form of the orebodies is an early feature; their length to width ratio has only been accentuated by deformation. They were elongate in plan prior to the earliest phases of folding (see section 5.4). Shearing has exaggerated the length of the orebodies in places. The closely associated Garnet Quartzite and B Lode Horizons are also roughly lenticular ribbons in general form and are folded by the earliest generation of folding (see Chapter 5). Ribbon-like ore positions lie parallel to similar elongate thickenings observed in the various sub-units of the ABMPG, in the Footwall Succession to the orebodies (e.g. Figure 4.2 and 4.3 and see later).

## Primary Features of Broken Hill Mineralisation - Orebody Scale

2L, 3L, 1 Lens Lower, 1 Lens Upper	A Lode Lower, A Lode Upper, B Lode, Southern A Lode (?), Southern 1 Lens (?)
Calcite-silicate-apatite-fluorite-sulphide banding (2L, 1LU & 1LL). Fluoritic horizon in 2L (southwest end) Fluorite is a component of calcitic banding. Apatite-rich bands form a component of calcitic banding.	Quartz-sulphide banding (ALU, ALL, BL)
Rhodonite layers (2L; 16-21 Levels, Pasmunco Mine, southwest end; & 3L in ML 15 & north-eastwards (particularly the British Mine and middle levels of North Mine)	Rhodonite layer (banded) (ALL)
Quartz-sulphide banding in 3 Lens & 1LU/1LL	Pyrrhotite zone in ALU/WAL (?)
Disseminated fluorite, quartz-rich and rhodonite layers (rhodonite in NE only) in 3 Lens (Northeast & southwestern ends of deposit)	Stratification of the BL orebody (the B Lode 'Complex')
Calcitic ore (2L style) development on northern limb of 3L, near southwestern termination (Pasmunco Mine)	Calc-silicate (hedenbergite) layer (originally calcite-rich zone?) in A Lode Lower
Rhodonite, fluorite & quartz distribution in North Mine 3L	Lenticular cross section of ore lenses (i.e. Linear 'mounds').
Layered galena (lead grade) distribution in British Mine & North Mine 3L (modified by D2).	Linearity of ore lenses (less affected by shear attenuation than 2L and 3L)
Lenticular ('mound shape') cross sections of ore lenses.	Bulk geochemical differences of ore lenses as reflected in gangue mineral assemblages; decrease in calcium and manganese content of mineralisation from 2L-1L to BL
Linearity of ore lenses (accentuated by shearing in 2L and 3L)	Increase in quartz content within sulphides upwards from ALL & especially from AL Upper.
Garnet quartzite (progenitor) , 3L (NE & SW end terminations & footwall).	Diminishing lead content from 2L to BL.
Pyrrhotite zone on northwestern margin 2L, South Mine to Pasmunco Mine	Relatively uniform percentage of zinc deposition as weight percentage of total mineralisation deposited in each lens (i.e. each ore lens has a similar volume of zinc).
Clastic metasediment tongues & interdigitation with 2L & branches (1 Lens) between 17 & 19 Levels Pasmunco Mine	
Fitzpatrick "Zinc Lode" (affinities uncertain but probably dislocated 3L segment)	
Possible association with underwall zone calcium-rich lithologies (southwest)	

**Figure 4.17:** Summary table of the recognisable primary features of the Broken Hill orebodies.

3L and 2L describe a boomerang-shaped arch in longitudinal section that extends for 8.5 kilometres, though 2L is dismembered in the central part of the field (Figure 4.14). The northeastern limb of the arch plunges to the northeast, at around 40 degrees (steepening to 70 degrees) at the northeastern end of the field. The southwestern limb plunges approximately 20 degrees at the southwestern end of the field. It thus defines an arch shape in longitudinal section, the apex of which occurs in the centre of the field (where erosion has exposed the orebodies). The plunge of 2L and 3L in the southwest end of the field is also observed in the B Lode Horizon (Western Mineralisation) and the 4.5 mineralisation (Figure 4.14).

The best means of conveying the complex geometry of these giant orebodies to the reader is to refer them to the digital maps contained in Appendix 1. Examine successive mine level interpretations and the progressive changes can be observed.

#### **4.7.3. No 3 Lens.**

No 3 Lens (3L) was the most economically significant orebody of the Broken Hill deposit, being the richest in terms of contained lead, silver and zinc. 3L is the only orebody that outcropped to any significant degree (the 'discovery' outcrop was 3L) and so was the main source of the rich oxidised silver ores that generated the original wealth of Broken Hill (see Chapter 6). It persists as a mostly unbroken zone of high-grade sulphide ore over a strike length of approximately 6.5 kilometres. It was the predominant high-grade ore resource for mines in the historic central and northeastern parts of the field, including the Central, BHP, Block 14, British, Junction, Junction North and North Mines. 3L only diminishes in economic importance in the Pasminco Mine, at the southwestern end of the field.

3L was known as the Southern Orebody by North Mine staff; as the Lower Orebody in the Junction and Junction North mines, and as the Main Lode in mines of the central region of the field (Block 14, BHP, Central and Block 10 mines). 3 Lens was named by Gustafson (1939) who recognised the continuity of the orebody throughout the mining field for the first time and Burrell (1942) confirmed that the quartz-rhodonite-fluorite gangue mineralogy was as characteristic of the 3L as were the Pb:Zn metal ratios that had been used previously to distinguish it from 2L.



The long strike length of 3L means that it passes through all of the structural regions of the mining field and it is therefore the most geometrically complex of the ore lodes at BH. With only two significant structural breaks in its entire strike length (British Fault and Globe-Vauxhall Shear), it is also the most continuous orebody of the field. The variations in this geometrically complex orebody can be examined by scrolling through the level maps presented in Appendix 1 (on the CD at rear of the thesis). Southwest of the BHP Mine, 3L diminishes in thickness and extent in an antipathetic relationship with the waxing of 2L in the same region (Figure 4.14).

The geometry of 3L has been modified by attenuation at high metamorphic grade in the lower levels of North Mine (below the 28 Level). The 3L and 2L orebodies are drawn out and attenuated while preserving their spatial relationship (see map NTH26 to NTH30 in Appendix 1 and see also Figure 5.26). In effect, they have been stretched, while preserving the F2 folded geometry as a drawn out isoclinal fold pair. The D3B quartz-sericite biotite phase of the Globe Vauxhall Shear Zone overprints and offsets the attenuated fabric of the orebodies and is later. This structure truncates the west dipping grain of the orebodies (see Chapter 5).

3L is composed of massive to banded, medium to coarse-grained sphalerite-dominated sulphide rock. Gangue minerals are usually dispersed throughout the sulphides but as will be described below, banding is present in some localities.

The mineralogy of 3L is variable, though not as complex as 2L, and the mineral complement is generally consistent throughout the mining field. Gangue distribution is not random. Various workers, such as Van der Heyden and Edgecombe (1990) have described the primary mineralogy of 3L (Figure 4.18). Andrews (1922) noted that in the BHP Mine, most ore being mined was rhodonitic ore.

Most workers have noted some calcite in 3L and Gustafson et al (1950) noted that calcite zones in 3L tend to have 2L metal ratios. Towards the southwestern termination of the orebody, in the Pasminco Mine, a strong 2 Lens-like zone develops (section 4.7.3.3). Some feldspar has also been noted as a gangue constituent of the orebody, probably because of the dismemberment of pegmatite intrusives in ore (observed in 2L by Webster, 1994a).

As in all of the BH orebodies, a simple list of the minerals that are found in each lens does not do justice to the textural variety that may be exhibited by each species, nor does it provide information about the distribution of these minerals. An understanding of the latter aspects of the mineralogy of these orebodies leads to a greater understanding of the structural history and primary stratification of the deposit.

*Figure 4.18. Mineral Complement of 3 Lens, as defined by various authors. Refer to Figure 1.3.*

Locality	Minerals in 3 Lens	Source
North Mine to Pasminco Mine (ZC Area)	Sphalerite, galena, pyrite (rare), loellingite (locally massive), pyrrhotite, chalcopryite (rare), fluorite (occasionally conspicuous, disseminated or patches), rhodonite (fine to medium grained), quartz (sparse) and calcite (rare).	Gustafson (1939)
Northeast Region	Galena, sphalerite, rhodonite, fluorite, quartz, garnet, chalcopryite, pyrrhotite, loellingite, arsenopyrite, gahnite, apatite, pyroxmangite, amphiboles, calcite, feldspar, bustamite, pyrosmalite	Plimer (1984)
Northeast Region	Sphalerite, galena, pyrite (very rare), arsenopyrite, loellingite, pyrrhotite & chalcopryite, rhodonite, fluorite, garnet, quartz (sparse), calcite (rare)	Henderson (1953)
Northeast Region	Rhodonite, fluorite, quartz, garnet	Johnson & Klingner (1976)
Central Region (Kintore Open Cut; ML 9, 10 and 11)	Galena, sphalerite, chalcopryite, arsenopyrite-loellingite, in blue-quartz garnet sandstone.	Van der Heyden & Edgecombe (1990).
British-Junction Region (Blackwoods Open Cut (ML 14 & 15)	Coarse-grained galena and sphalerite, with minor chalcopryite, arsenopyrite-loellingite and pyrrhotite in a rhodonite-spessartine-quartz-fluorite-apatite gangue.	Van der Heyden & Edgecombe (1990).
Southwest Region? (Pasminco Mine ?)	Sphalerite, galena, quartz, rhodonite, fluorite (pink) & garnet.	King & O'Driscoll (1953)
Southwest Region	Sphalerite, galena, quartz, fluorite, rhodonite, garnet,	Plimer (1984)
Southwest Region	Quartz, fluorite, rhodonite, garnet	Haydon & McConachy, (1987)

4.7.3.1.     *Grade and tonnage of 3 Lens.*

3L is the richest orebody at Broken Hill. However, concentrator returns and ore reserve figures have never been comprehensively compiled for all of the former mines of the field to produce a definitive tonnage and grade figure for the whole orebody. The orebody is also truncated at depth by shearing at the northeastern end of the field,

further complicating the task of calculating a definitive total pre-mining resource figure for the orebody. However, estimates of 3L ore grade have been calculated by various authors for separate regions of the field. They are tabulated below (Figure 4.19).

**Figure 4.19.** Table showing calculated lead-zinc-silver grades of the 3 Lens orebody in various regions of the Broken Hill mining field.

Location	Pb%	Ag g/t	Zn %	Data Source
2K Zone (Inferred 0.6MT)	18.0	350	17.0	Morland & Webster (1998)
NE Region	15	231	12	King and O'Driscoll (1953)
NE Region	17.6	306	15.1	Henderson (1953)
NE Region	17	306	15	Carruthers (1965)
NE Region	15	300	13	Johnson and Klingner (1976)
ML 12	9	284	6.6	Black (1953)
ML 11	15	398	14	King and O'Driscoll (1953)
ML 11	19	496	18.5	Black (1953)
ML 9&10	15	459	17	King and O'Driscoll (1953)
ML 9&10	14	416	16.2	Black (1953)
ML 8	16.8	398	20.8	Black (1953)
ML 7	16.7	367	22	Black (1953)
Central area	15	459	17	Carruthers (1965)
SW Region	15	336	18	Pratten (1965)
SW Region	11	245	14	Carruthers (1965)
SW Region (mining grade)	7.8	169	11.9	Haydon and McConachy (1987)
SW Region	11	200	15	Johnson and Klingner (1976)
ZC section 31	15	336-367	18	O'Driscoll (1953)
SW Region (2L-like ore, 3L)	15	245	12	O'Driscoll (1953)
"Typical"	18	352	20	Gustafson et al (1950)
<b>Average</b>	<b>14.8</b>	<b>333</b>	<b>15.8</b>	

Burton (1990) estimated that 3L originally consisted of approximately 76 million tonnes of ore. However, this figure is probably understated. Production figures from 2 Lens and 3 Lens are muddled, especially for the North and NBHC (Pasminco) mines where they were frequently mined together. There is also a considerable tonnage of 3L ore in the 'Southern Panel' of the Pasminco Mine (Webster, 1996a), which has traditionally been included with 2L ore as "Lead Lode" mineralisation (Figure 4.20). This occurrence was never specifically classified as 3L because 2L and 3L were referred to as the "Lead Lode" in the NBHC part of the Pasminco Mine. The total pre-mining tonnage figure for 3L is further complicated by the lack of data or the confused production reporting of the mines. This figure remains to be calculated and it should be possible from the available detailed records. What is apparent is that while 3L is second to 2L in total tonnage, it has produced more metal and was, historically, the most consistent and widespread ore source at Broken Hill.



SOUTHWEST

NORTHEAST

**Stacked level plans showing stratigraphic relationships between  
1 Lens, 2 Lens and 3 Lens on the 17, 18 and 19 Levels,  
Pasminco Mine.**

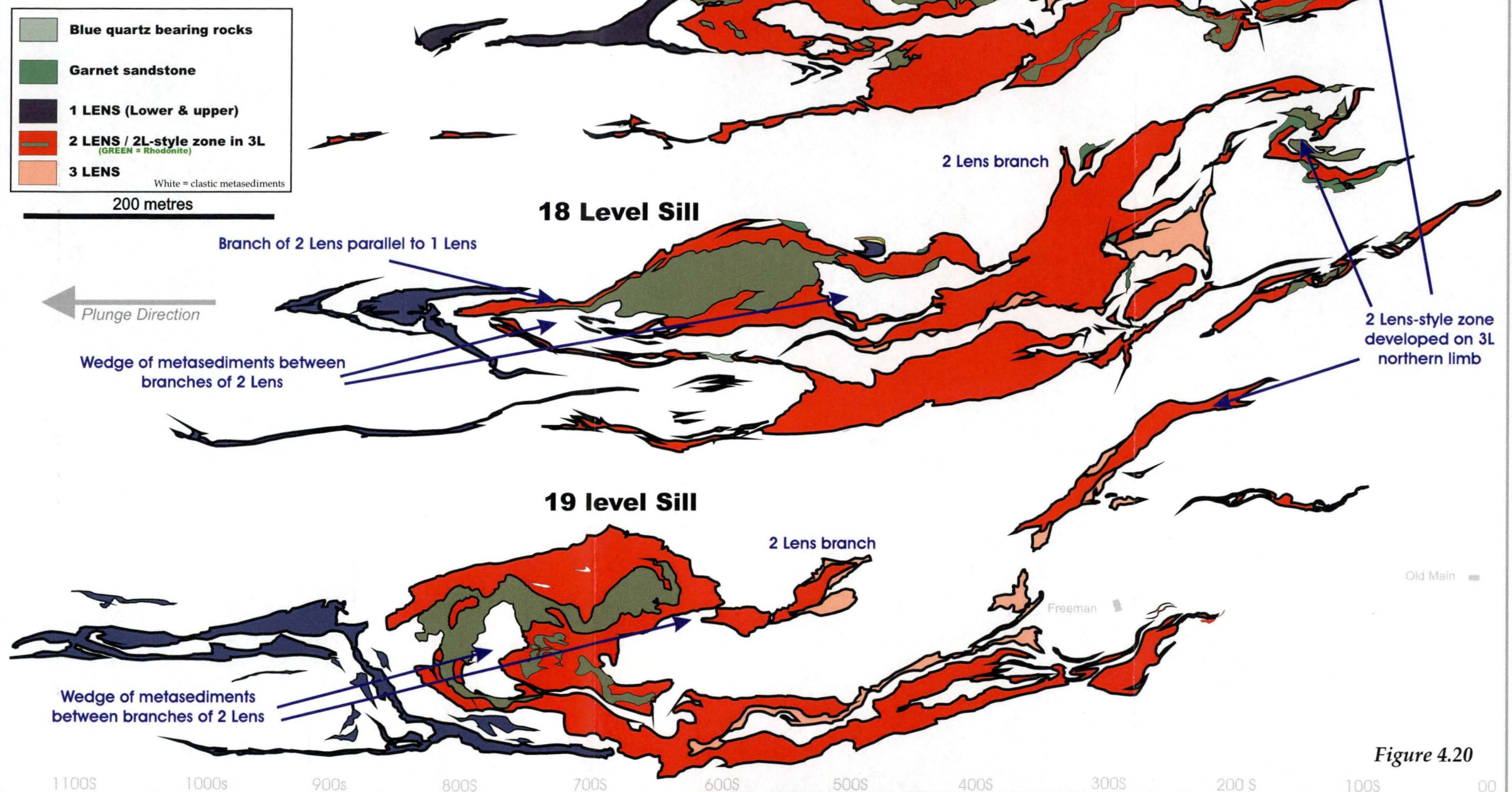


Figure 4.20

4.20b

Reconstruction (pre D2)

Schematic: Reconstruction of the relationships of 2 Lens and 1 Lens Group around the 18 level Pasminco Mine

**Figure 4.20.** Stacked level plans showing the stratigraphic relationships between 3L, 2L and the 1L orebodies in the region of the 17 to 19 Level sills, Pasminco Mine. 2 Lens becomes stratigraphically complex in the region of the 18 Level, developing at least three branches that are interbedded with clastic metasediments. Two of these branches are 1 Lens Lower and 1 Lens Upper. Rhodonite layers become prominent within 2L in this region. A calcite and rhodonite-rich zone develops within 3 Lens in this same region of the deposit.

**4.20b.** Schematic reconstruction of the pre-D2 relationships between 3 Lens, 2 Lens, 1 Lens Lower and 1 Lens Upper, between the 17 & 19 Levels of the Pasminco Mine.



No 3 Lens seems to show a general decrease in lead (and silver) grade relative to zinc grade, along-strike from the North Mine (northeast) to the Pasminco Mine (southwest) (e.g. Plimer, 1984; Webster 1994a). In the generally accepted definition of "Lead Lodes" and "Zinc Lodes", still used at Broken Hill, where zinc percentage is greater than lead, 3L is technically a "Zinc Lode" in the Pasminco Mine. The classification of orebodies at Broken Hill is discussed more fully at the end of this chapter.

The change in the relative percentages of lead and zinc that is observed in 3L occurs over a strike extent in which the orebody changes in several significant ways, including geometrically; texturally and structurally. In this interval of several kilometres, the intensity of F2 folding and D3A attenuation diminishes and the F2 folded geometry of the orebody becomes more open and simple. It cannot be stated with certainty that the higher lead grade at the northeast end of the deposit is a primary depositional feature of the orebody or whether it is the result of structural upgrading of the ore. However, there has been a considerable redistribution of galena during D2, forming an axial planar, galena-defined S2 fabric within the ore (which is recorded in lead grade mapping). Extensive recrystallisation of gangue minerals has also taken place within the orebody (often forming gem quality rhodonite and garnet crystals, which are very common). The geological and textural changes in the northeast part of 3L certainly make structural upgrading of lead grade a possibility.

#### 4.7.3.2. *Orebody Margins.*

Throughout its strike length, 3L has remarkably sharp ('knife-edge') contacts with adjacent metasediments and there are no obvious transition zones between very sulphide-rich ore and wall rocks. However, while the sulphide-metasediment contacts are sharp, there is often a zone of strongly developed blue quartz alteration developed in the metasediments and lode rocks at the orebody margins; particularly in the footwall and in the region of metasediments separating 2L from 3L. The blue quartz alteration zone is most markedly developed in the northeastern part of 3L, particularly in North Mine where it is best developed in the footwall of 3L. The zone reached mineable proportions and grades only in the northeastern part of the deposit, where it was a recognised ore type (siliceous ore, or mineralised quartzite), though geologically not a part of the original orebody. Marginal blue quartz alteration and silicification is only weakly developed, or absent in the central and southwestern end of the field (e.g. O'Driscoll, 1953). The association between 3L and thick zones of blue quartz and

sulphide-veined alteration of wall rock metasediments is unusual for the BH mining field. Most other orebodies possess variably developed siliceous margins (usually less than 1-2m) but they are not developed to the extent of those adjacent to 3L in the North Mine.

In such marginal alteration zones, metasediments (and lode rocks such as garnet sandstone) have been silicified to produce blue quartz rocks (Figure 4.10e). Blue quartz alteration zones overprint metasedimentary bedding and banding; preserving the fabric but transgressing the general trend of fabric (e.g. refer to Figures 4.22, 4.23 & 4.24 for detailed interpretations, these maps are contained in the separate map folder). Mobilised sulphides have impregnated the silicified rocks. The geometry of the blue quartz alteration zone in North Mine (where known) is shown in all of the North Mine level plans in the accompanying digital map set (Appendix 1).

It is possible that the blue quartz zones formed as a syn-depositional 'footwall alteration' as 3L was formed, because these zones appear to be folded by the F2 folds that deform the orebodies. However, there is much evidence that suggests that the siliceous alteration is syntectonic and probably syn-D2. The altered metasediments are extensively impregnated and veined by mobilised sulphides, of a style and mineralogy that suggests they were emplaced during D2. D1 pegmatitic segregations are often incorporated in the alteration zones, where they are variably altered to blue quartz. 'Garnet sandstone' is also incorporated within the altered zones. Blue quartz alteration is also only weakly developed in the southwestern and central parts of the mining field where F2 folding and transposition was much less intense. The blue quartz alteration zone is most strongly developed in association with intense F2 folding and transposition and the zones form a halo around intensely transposed and folded 3L (and 2L) ore, with a well developed S2 fabric; suggesting that it was formed syn-D2. Much narrower but similar alteration zones are observed on the contact of B Lode in the Southern Cross area of the Pasminco Mine, which also overprint D1 lode pegmatite on a large scale. Therefore, the extensive blue quartz alteration halos surrounding 3L in the northeastern end of the deposit are interpreted to be a D2 syn-tectonic features that was focussed on the orebody footwall, and not a footwall alteration zone formed during the original deposition of the sulphides.

Narrow (usually <1m) garnetiferous "rinds" or "rims" are commonly developed at the contact between 3L and clastic metasediments. Most of these garnetiferous rims are

interpreted to be syn-metamorphic in origin, as has been observed for 2L and 3L (e.g. Jones, 1968; Maiden, 1972; Billington, 1976; Spry, 1978; Webster, 1996a). Most probably formed during D2,

'Garnet sandstone' is common in association with the footwall of 3L throughout its strike length (e.g. Jaquet, 1894). It outcrops in this position at surface in the Browne Shaft brace area (Figure 5.1 but see also Figure 5.16 for detailed geology of outcrop) and was observed in the upper levels of the British, Junction and North Mines by mine staff. Garnet sandstone was a major gangue component of the 3L ore mined in the BHP Mine, where it was particularly well developed (Andrews 1922; Van der Heyden and Edgecombe, 1990) (e.g. refer to map BHP3 in Appendix 1 and to Figure 5.17a). Garnet sandstone is also well developed on the 3L contact at the far southwestern end of 3L, on Stope Section 26 of the Pasminco Mine, where it carries high-grade gold and silver values (Webster, 1994a) (e.g. Figure 4.9). The deposit-scale continuity of this zone is not determined but it is widespread in this position throughout the field and is probably continuous. Garnet sandstone is interpreted to represent altered (metasomatised) garnet quartzite of a similar type to the unaltered varieties seen in the Pasminco Mine, several kilometres to the southwest.

A narrow (probably less than 1 metre) occurrence of pyrrhotite occurs on the northern and northwestern margin of 3L throughout the South Mine. This zone was recorded as being "pyritic" by the mining personnel who provided the information to Andrews (1922).

Throughout much of the North Mine, 3L and 2L are strongly folded within a transposed series of F2 folds (see Chapter 5). Within the fold hinges, high-grade ore from 2L is often juxtaposed with ore from 3L (refer to maps NTH1 to NTH30 in Appendix 1). Overprinting syntectonic blue quartz silicification is focused within the narrow region of clastic metasediments between the two orebodies and it is heavily veined by mobilised sulphides. In this zone of altered and veined metasediments, it is difficult to delineate 3L from 2L, or altered metasediments, based on gangue mineralogy (silicification overprints everything) (refer to Figures 4.22, 4.23 & 4.24 for detailed interpretations, contained in separate map folder). In such areas of the North Mine, the orebodies were mined together (see Figure 4.14).

#### 4.7.3.3. *Orebody Terminations.*

The contacts of the high-grade sulphide ore of 3L are sharply defined. Transitional zones with the adjacent metasediments and lode rocks are rare, even where the marginal, siliceous, blue quartz altered zones are most strongly developed. Wall rock alteration may result in the indiscriminate silicification of any rock type adjacent to the orebody but the sharp boundary with the sulphide rocks remains clear. This gigantic orebody does not 'fade' into the surrounding stratigraphy along its distal margins but ends abruptly. A localised unit of garnet quartzite develops in the footwall of 3L, near the southwestern termination, in the Pasminco Mine. Surface mapping shows that the thin 3L margin that reaches surface in the Browne Shaft area has a significant development of garnet sandstone/garnet quartzite in the footwall (Gustafson, 1939; D. Larsen pers comm., 1995) (see section 5.5.2.2 for a detailed description of this outcrop). In the Pasminco Mine, bodies of garnet sandstone become more prominent on the southern and northern sides of 3L and at approximately the 18 to 19 Levels of the ZC section of the Pasminco Mine, 3 Lens dies out down dip into a garnet sandstone horizon.

Down dip to the north and south the 3L position is unmarked by a recognisable horizon, as is the case beyond the southwestern termination. There is no recognisable mineralised horizon or lode rock zone marking the 3L position within the Lode Sequence beyond the main sulphide occurrence.

3L exhibits peripheral mineralogical variations at the southwestern end that probably reflect terminal 'facies' changes. The orebody develops a zone of 2L style banded calcite and rhodonite-bearing mineralisation along the northern limb, which is best developed between the 18 and 19 levels of the Pasminco Mine (Figure 4.20). O'Driscoll (1953) recognised this zone as becoming prominent southwest of Cross Section 30 (the ZC Main Shaft section). In this region, 3L becomes indistinguishable from 2L (developing a separate zone of 2L-like mineralogy), excepting an apparent abundance of fluorite gangue, and apart from its stratigraphic position within the Lode Sequence and by its close association with a well-defined quartz-fluorite 3L zone that persists on the footwall.



A distinct quartz and fluorite bearing 3L zone persists as a distinct entity or zone throughout most of the Pasminco Mine, becoming an important element of the 'Southern Panel' mining area between the 21 and 24 Levels of the Pasminco Mine (Figure 4.9). 3L may partially merge with 2L as well, persisting as a 3L-like zone of fluorite-bearing massive sulphides in 2L.

Previous workers have suggested that as 3L wanes, it merges with 2L, finally ceasing to be a distinguishable ore horizon. This interpretation has led to the term "lead lode" being used in the NBHC area of the Pasminco Mine (e.g. Webster, 1994a), a mining area where the distinction between 2L and 3L was uncertain. However, the two orebodies remain mineralogically, and largely stratigraphically separate throughout this mine (e.g. see maps NBH13 to NBH21 in Appendix 1). The 2L-style ore that develops within 3L causes the confusion.

The northeastern end of 3L is structurally dislocated by the Globe-Vauxhall and Western Shear system. 3L and 2L become progressively more attenuated with depth below the 26 Level of North Mine, despite retaining their spatial relationship and preserving the F2 folded geometry. Below the 30 Level, the orebodies are dislocated by the easterly dipping Globe-Vauxhall shear but remake as the "Fitzpatrick Orebody". The Fitzpatrick Orebody, comprising mostly 3L ore (with some 2L), is in turn truncated at depth by the Western Shear. Although 3L mineralisation was located by drilling at depth beyond the Western Shear (the "2K Zone") (Morland and Webster, 1998) its extent is unknown. 3L remains open at depth.

#### **4.7.3.4.     *Stratification of 3 Lens (S0).***

Like all other BH orebodies, 3L is strongly banded in places and this banding is considered to mostly be a primary feature of the ore (S0). Maiden (1972) described banding within high-grade 3L quartz ore in the Pasminco Mine as consisting of sharply defined layers of fine grained quartzite with little disseminated sulphides, alternating with layers of sulphide containing many minor amounts of quartz-garnet gangue. He observed that the banding in high-grade 3L was similar to that in the low-grade quartz ore and that sulphide mobilisation across the layering was more commonly seen than in low-grade ore. He attributed this to the higher concentration of sulphides.

In all areas of 3L that it has been possible to examine, a similar sulphide-gangue relationship exists. Gangue minerals, such as well-developed rhodonite-bustamite crystals, fluorite crystals, spessartine garnet crystals and patches and blobs of blue and clear quartz, are evenly distributed throughout the coarse equigranular sulphide matrix. However, despite their dispersal at the mine level or stope scale, they form distinct mineralogical zones (Figure 4.21, 4.22, 4.23). These zones are consistently observed throughout the North Mine, within the South Mine (Figure 4.25), and to a lesser degree in the Pasminco Mine (e.g. Figure 4.9). They are folded by F2 folds and are transgressed by a galena-defined S2 foliation. The gross distribution of major gangue minerals in 3L is therefore interpreted to reflect a primary layering in the orebodies (S0). This layering has subsequently been texturally modified by redistribution of the sulphide constituents of the orebodies and a large-scale syntectonic retexturing of the ore. Between the 200 and 500 Levels of the British Mine, massive to weakly mineralised rhodonite zones form the best-defined layering in 3L, within F2 fold hinges (Figures 4.26). Rhodonite also forms large, low-grade masses in the keels of attenuated F2 folds in the North Mine (Figure 4.14 and 4.22). Lead grade is also stratiform in distribution in 3L in the British Mine and is less affected by D2 mobilisation than it is in the North Mine (Figure 4.27; compare with Figures 4.22 to 4.24).

The distribution of rhodonite, fluorite and quartz is not random within 3L but defines distinct zones within the orebody (Figures 4.21 to 4.26). Even though these gangue constituents are dispersed throughout the sulphides, they all define distinct, possibly mutually exclusive zones (layers) within the sulphides throughout the strike length of 3L; including the North, British, South and Pasminco Mines (Figures 4.22 to 4.24, contained in separate map folder). Rhodonite appears to be weakly developed, or absent, from the southwestern part of 3L in the Pasminco Mine but the layered quartz and fluorite zones are present (Figure 4.9a).

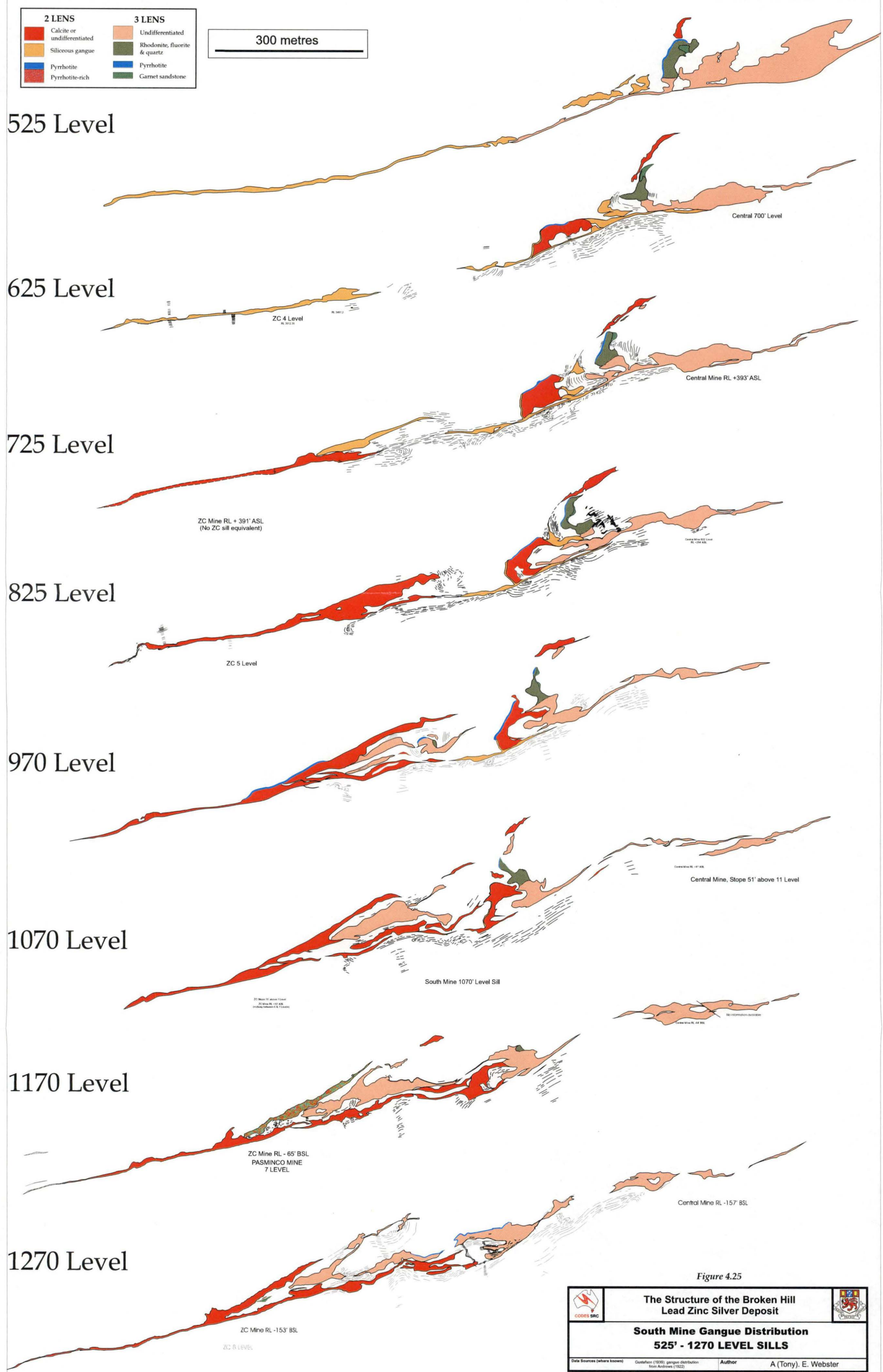
Primary (disseminated) quartz seems to be antipathetic to rhodonite in its distribution, occupying the greater part of the upper (northern side) of 3L in the North Mine section of the orebody. Quartz is also associated with the highest lead grades in 3L in North Mine. Rhodonite occupies the footwall of the orebody and occasionally forms massive pods of poorly mineralised material within the infolded feels of folds. Fluorite defines a distinct zone between the lower rhodonite and the upper quartz zones, having an

apparently layered distribution (Figures 4.22 to 4.24, all contained in separate map folder).

Rhodonite forms distinct, massive layers in 3L in the British Mine where it defines a horizon of low-grade (un-mined) material that is folded around the hinge of the British Synform preserved in the British Shoot (Figure 4.26). The form of this layer is comparable to that seen in 2L in the Pasminco Mine (Webster 1993, 1994a) but is more clearly distinguishable as a definite layer. Rhodonite-bustamite also occurs as base metal barren and weakly mineralised pods within attenuated synformal fold keels in the footwall of 3L in North Mine (e.g. Figure 4.22, contained in separate map folder, & 4.14). Similar zones exist in 3L on the western limb of the orebody in the Block 14 mine area and throughout 3L in the South and Central Mines where defined quartz and rhodonite-bustamite zones have been mapped. No such zones are observed in 3L the Pasminco Mine however.

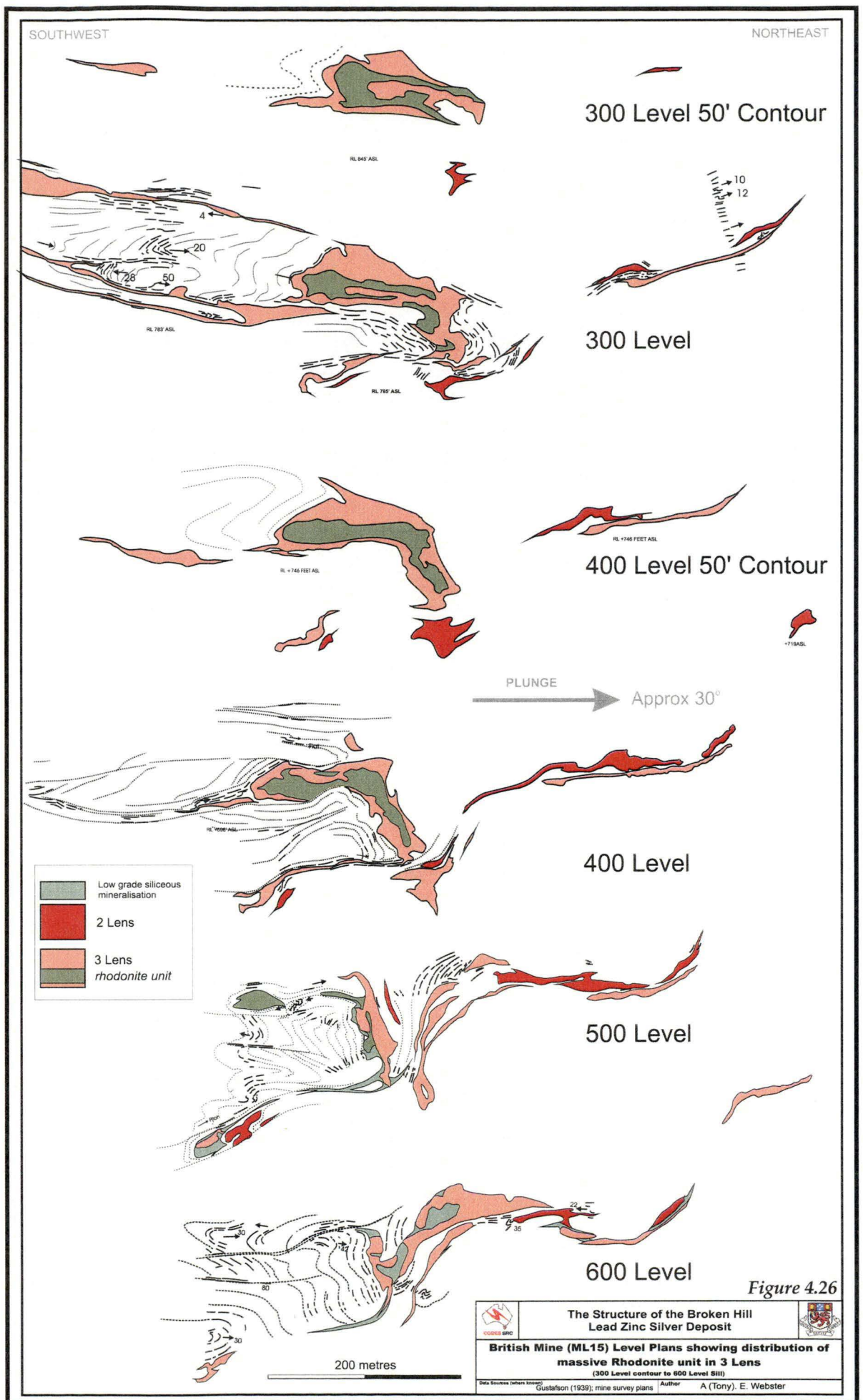
Figure 4.21. Primary zones recognised within No 3 Lens (see Figures 4.22, 4.23, 4.24, 4.25 and 4.9).

Zone	Where known	Description
<i>Quartz Zone</i>	<ul style="list-style-type: none"><li>• North Mine – all levels below 24 sill</li><li>• South Mine</li><li>• Pasminco Mine</li><li>• Probably in the British Mine</li></ul>	A sulphide-rich zone in which disseminated quartz is the main gangue constituent. This zone persists throughout the strike length of the orebody & corresponds to the richest base-metal accumulations in 3L (& possibly the BH mining field). Comparable to the primary quartz-rich zone that occurs on the upper contact of 2L in the Pasminco & South Mines & is comparable to high grade B Lode.
<i>Fluorite Zone</i>	<ul style="list-style-type: none"><li>• North Mine (below 25 Level)</li><li>• Pasminco Mine (Southern Panel - stope section 26 &amp; ZC area)</li></ul>	A fluorite-rich zone, which did not contain rhodonite & probably did not contain primary quartz. It was also sulphide-rich, in a similar manner to the Quartz Zone.
<i>Rhodonite Zone</i>	<ul style="list-style-type: none"><li>• North Mine (disseminated &amp; massive). Massive rhodonite</li><li>• British Mine (well-defined massive layer)</li><li>• South Mine (disseminated zone on northern limb of orebody)</li></ul>	<p>A thick zone of disseminated rhodonite located on the footwall side of the orebody. Often with Pb-Zn depleted or barren, manganese-silica masses in fold keels (11 to 20 &amp; around the 26 Level. A massive weakly to poorly mineralised layer is also well defined between the 200 &amp; 500 Levels of the British Mine.</p> <p>A disseminated rhodonite zone is focussed on the northern limb of 3L throughout the South Mine, particularly between the 525 &amp; the 1070 Level.</p>
<i>Banded Calcite Ore Zone</i> ("2 Lens" style zone)	<ul style="list-style-type: none"><li>• Pasminco Mine, below 17 Level</li></ul>	Developed on northern limb of 3L below the 17 Level. See text
<i>Pyrrhotite zone</i>	<ul style="list-style-type: none"><li>• Northern limb of 3L, South Mine &amp; Pasminco Mine.</li></ul>	A narrow marginal 'rind'. Uncertain if this is a true primary feature of the orebody or generated by metamorphism and deformation.



**Figure 4.25.** Plans of the major levels (525 to 1270 Levels) of the South Mine (southwestern region of the mining field), showing the distribution of the main gangue species within 2 Lens and 3 Lens. Geology interpreted from the data of Gustafson (1939) and gangue distribution from Andrews (1922). Where 3 Lens is shown in pink, it is assumed to contain a siliceous gangue.





**Figure 4.26.** Sequence of level plans of the British Mine (300 Level contour to 600 Level sill) showing the distribution of a massive rhodonite unit (S0) in 3 Lens. The layer is deformed by the northeast plunging F2 British Synform. Interpreted from the data of Gustafson (1939) and mine survey plans.

Lead grade distribution is also not random in 3L. The distribution of lead, as mapped by North Mine geologists, shows that there is a predominant stratigraphic, rather than a structural distribution of galena in 3L. Lead grade copies the layered distribution of the quartz, fluorite and rhodonite layers (Figures 4.22 to 4.25). While the galena has been extensively redistributed to form a syntectonic (S2) fabric in the orebody in North Mine, the distribution of lead is still mainly controlled by an earlier, probably primary, depositional control that predated D1 pegmatite intrusion.

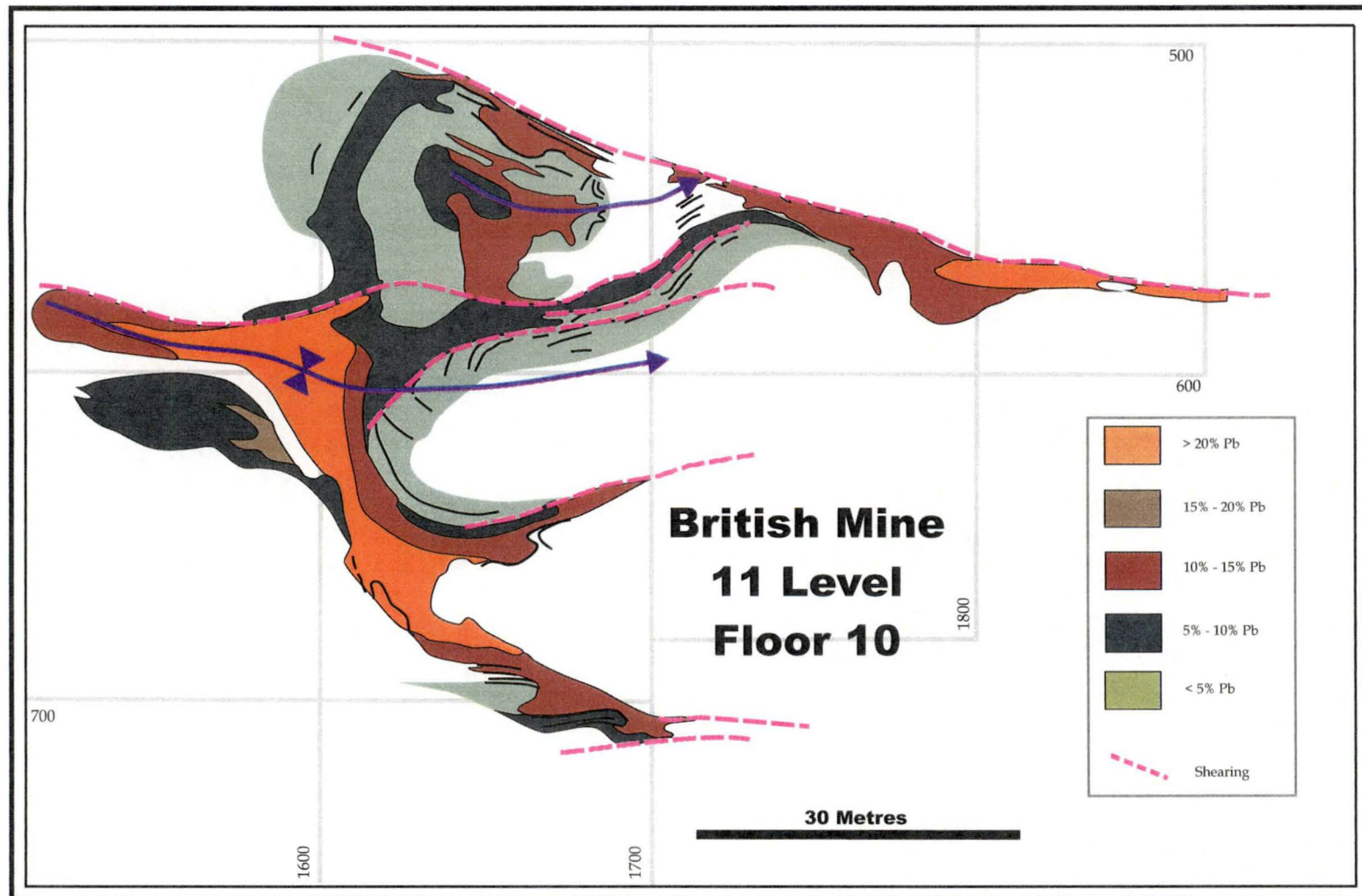
The lead-defined S2 and S0 fabrics have not been confirmed in 3L in the Pasminco Mine but evidence from 2L (see below) suggests that the effects of D2 were not as pervasive in the central and southwestern parts of the mining field as they were in the North Mine. The pervasive S2 lead grade fabric is not observed in 3L in the British Mine (Figure 4.27; compare with Figures 4.21 to 4.23) and appears to be a phenomenon localised in the northeastern part of the mining field.

The most significant stratigraphic features of 3L are summarised in Figure 4.28b.

#### 4.7.3.5. *'Zinc Lode' Mineralisation in North Mine.*

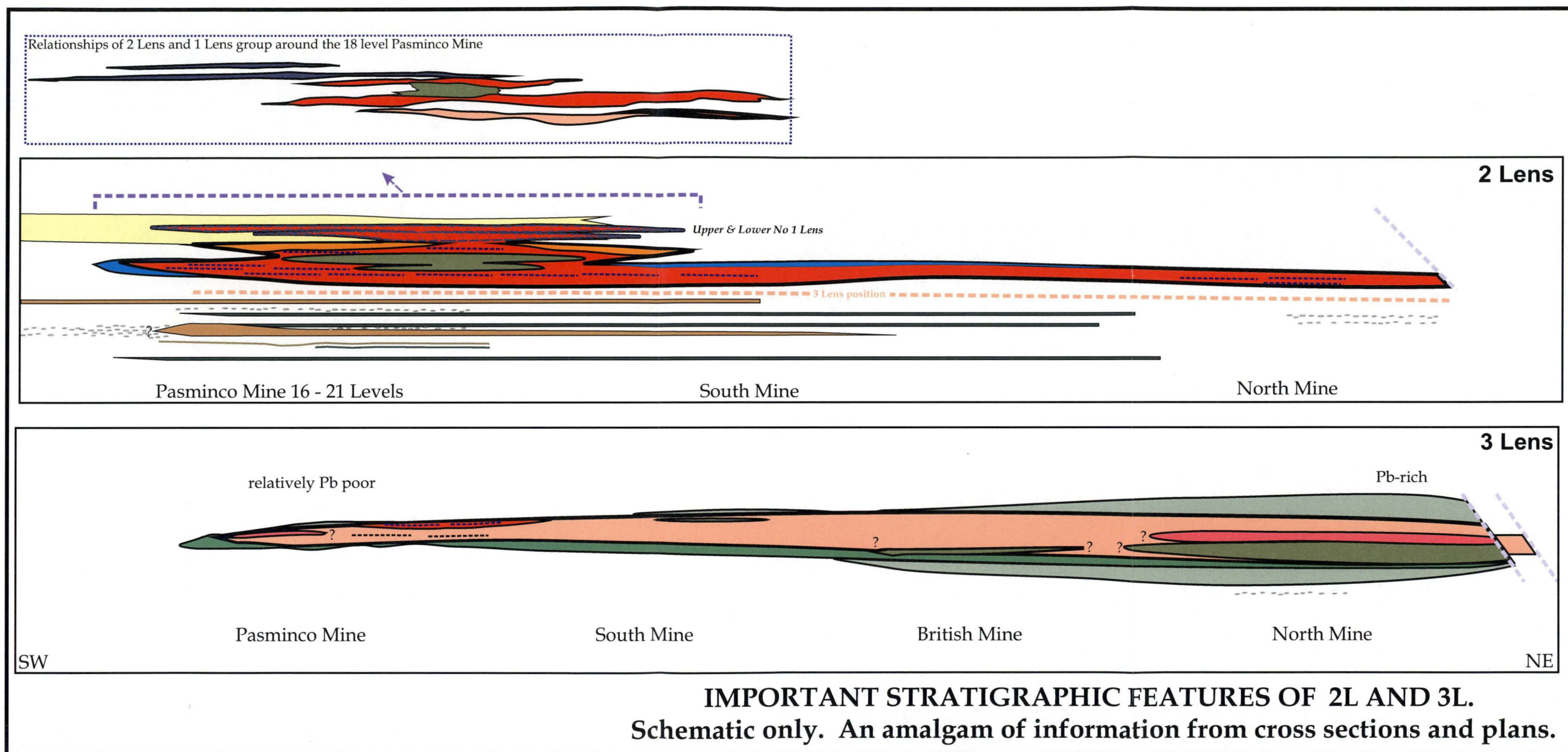
'Zinc Lode' style mineralisation has been identified and mined in the Fitzpatrick area of North Mine and was described by Aitcheson (1993) and D. Larsen and P. Jackson (unpublished data, 1993). Approximately 40,000 tonnes of zinc-rich ore was mined from this body, which was known as the Fitzpatrick Zinc Lode. The mineralisation in the Fitzpatrick area is of uncertain stratigraphic affinity and is probably an attenuated and dislocated segment of 3L, though this interpretation requires confirmation (see map NTH36 in Appendix 1).

Various other zones of so-called "zinc lode" mineralisation are known in the vicinity of North Mine. Weak mineralisation lying to the north of the main orebodies was described as "1 Lens" by Gustafson (1939) and a zone defined in the upper levels of the North Mine was defined as Zinc Lode mineralisation by D. Larsen and P. Jackson (unpublished data, 1993), among others. These examples could possibly occur in a segment of B Lode Horizon, or they could be mineralisation within the 4,5 Horizon. It is unlikely that the northeastern occurrence of "Zinc Lode" style mineralisation, to the north of the main orebodies, can be equated with the 1 Lens position of the Pasminco Mine. Their stratigraphic affinities are uncertain (see map NTH36 in Appendix 1).



**Figure 4.27.** Lead grade distribution (S0) in 3 Lens, deformed by F2 folds. British Mine 11 Level, Floor 10. The strong S2 fabric defined by lead grade observed in 3 Lens further to the northeast (in the North Mine) is not apparent in this part of the orebody, or to the southwest. Compare with Figures 4.22, 4.23 and 4.24. Modified after Gustafson (1939).





**Figure 4.28.** Cartoons showing the important stratigraphic features of 2 Lens (above) and 3 Lens (below). Unless otherwise shown, 3L has a quartz gangue. The inset diagram at top is reproduced from Figure 4.20 and shows details of the relationships between 2 Lens, 3 Lens and the 1 Lens orebodies in the Pasminco Mine. Colour scheme as per standard geological legend. Important stratigraphic features of 2L and 3L. Schematic only. An amalgam of information from cross sections and plans. Not to scale.



**4.7.4. No 2 Lens.**

No 2 Lens (2L) is probably the largest orebody, in terms of total contained ore tonnage, of the nine important ore horizons currently defined at Broken Hill. It was, until recently, the largest and most important ore source at the southwestern end of the field (e.g. O'Driscoll, 1953, Webster, 1994a). It extends for a known strike length of 7 kilometres and prior to mining contained well in excess of the 83 million tonnes of mineable ore (Burton, 1990). In addition, possibly 1.8 million tonnes of 2L was removed by erosion (see Chapter 6). 2L was known as the Northern Orebody in the North Mine and as the Eastern Lode in the BHP, Central and Block 10 mines. It was mostly absent from the Block 14 mine. 2L is the predominant lead-rich orebody in the NBHC section of the Pasminco Mine where forms the bulk of the "Lead Lode" (e.g. Webster, 1994a).

An estimate of the average lead, zinc and silver grades for 2L is more difficult to determine than for 3L because there are few figures available. 2L was only weakly developed in the centre of the mining field and was therefore a less important ore source. It was also acknowledged to have more consistent lead and zinc grades than 3L, so there was less need to record variations. As a result, there are less documented average grades available for different regions of the orebody (Figure 4.29). A definitive average grade for this orebody is therefore not possible to calculate, despite the fact that the data probably exists in mining company records to do this.

*Figure 4.29. Table showing calculated lead-zinc-silver grades of the 2 Lens orebody in various regions of the Broken Hill mining field.*

Location	Pb%	Ag g/t	Zn %	Data Source
NE Region	14.7	89	11.3	Henderson (1953)
SW Region (mining grade)	16.4	118	12.4	Haydon and McConachy (1987)
SW Region (typical medium to high grade ore)	20	122	14	O'Driscoll (1953)
SW Region	20	122	14	Pratten (1965)
"Typical"	14	100	11	Johnson and Klingner (1976)
<b>Average</b>	<b>17</b>	<b>110</b>	<b>12.6</b>	

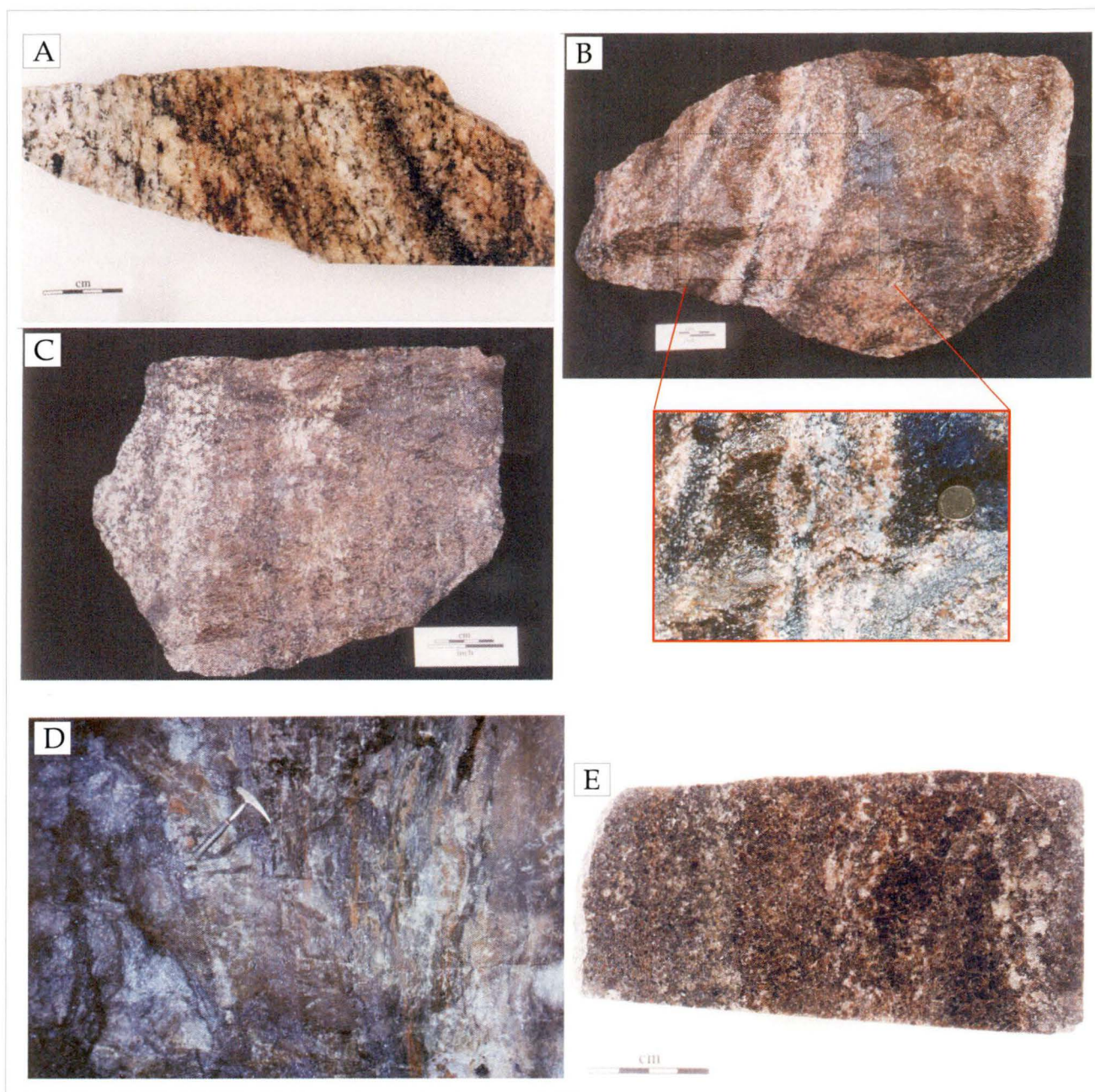
Silver was usually about one fifth of the lead percentage in 2L, however, there was a marked change in this relationship in the southwestern portion of the Pasminco Mine where silver was typically one third of the lead percentage. This rise in silver coincided with the appearance of scattered pink fluorite in the ore (O'Driscoll, 1953).

The mineral complement of 2L is diverse, with a variety of silicate, calc-silicate and other minerals present as gangue species. Galena and sphalerite are the predominant sulphides (Figure 4.30). The distribution of gangue minerals and sulphides is not random and the orebody is strongly stratified (Webster, 1994a; 1996a). In the southwestern region, 2L is composed almost exclusively of a banded sulphide-calcite rock with interbanded layers of lead-zinc depleted (probably barren) manganiferous siliceous rock (predominantly rhodonite). This aspect of the orebody is discussed more fully below (see section 4.7.4.8). 2L was observed to have a similar mineralogy to 3L in both the Kintore (BHP/Central Mines) & Blackwoods (British/Block 14 Mines) open cuts (Van der Heyden & Edgecombe, 1990).

**Figure 4.30.** *Mineral Complement of 2 Lens, as defined by various authors.*

Locality	Minerals in 2 Lens	Source
North Mine	Sphalerite, galena, chalcopryrite (minor), pyrrhotite, pyrite, quartz, calcite, rhodonite (very minor), manganhedenbergite, and fluorite (occasional).	Henderson (1953)
All	Galena, sphalerite, chalcopryrite (minor), pyrrhotite, pyrite (especially on northern contact in ZC). Sulphides rarely comprise more than 50% of many large stope areas. Calcite (less abundant in the British Mine) and/or quartz, rhodonite (coarse-grained local & small massive patches) and fluorite (rare & always green or white; never red or brown).	Gustafson (1939)
All	Calcite, rhodonite, bustamite, manganhedenbergite, roepperite, quartz, garnet, fluorite, apatite.	Johnson & Klingner (1976)
All	Calcite, rhodonite, bustamite, "manganhedenbergite", knebelite, quartz, garnet, fluorite, apatite.	Haydon & McConachy, (1987)
All	Galena, sphalerite, calcite, bustamite, manganhedenbergite, rhodonite, chalcopryrite (minor), pyrrhotite, loellingite, arsenopyrite, garnet, quartz, Mn olivines, feldspars, micas, amphiboles, staurolite, ilvaite, vesuvianite, johannesenite.	Plimer (1984)
Southwest	Galena, sphalerite with minor pyrrhotite & chalcopryrite. Calcite, quartz, rhodonite, hedenbergite, fluorite (pink or brown) and apatite (green).	O'Driscoll (1953)
All	Galena, sphalerite, calcite, quartz, garnet, feldspar (green or grey). <i>Bustamite and other "lime-manganese" silicates are common at the southwestern end.</i>	King & O'Driscoll (1953)

One of the most remarkable features of 2L is that it is the largest known accumulation of calcite in the Willyama Supergroup (WSG). Zones within 2L may be essentially composed of marble (Figure. 4.31a). Calcite is exceedingly rare in the WSG, with



**Figure 4.31.** Banding (S0) within the Broken Hill orebodies interpreted to be S0.

**a.** Hand specimen (polished slab) of 2 Lens calcite rich ore (sulphide-bearing marble) from North Mine (locality unknown). Banding is defined by sphalerite + \- galena (dark minerals) and calcite (white).

**b.** Large hand specimen of coarsely banded calcite (white)-rhodonite (pink)-sphalerite/galena (black) rich ore, from 2 Lens, 21 sub-level, NBHC area of Pasminco Mine. Insert outlined in red shows a detail of the banding in this specimen. From Panel 14, "Go Go stope", 21 Crown Pillar area, of the Pasminco Mine (NBHC area).

**c.** Hand specimen of sulphide-rich banded calcite ore from panel 12a, Go Go stope, Pasminco Mine 20 Level. This specimen contains a higher proportion of sulphides than specimen B and also contains silicates (garnet and rhodonite). The proportion of sulphides varies within the banded calcite ore but the variations tend to define layers within the orebody, rather than random patches.

**d.** Development face showing banded A Lode Lower. Banding defined by fine-grained garnet, (orange), quartz, sulphides with some pegmatitic segregations parallel to S0.

**e.** Polished slab of 2 Lens sulphide-silicate rich banded calcite ore, 14.8m contour, 20 level, Pasminco Mine (NBHC), 12 Level Pasminco Mine showing sulphide and silicate-rich banded calcite ore. Calcite = white, garnet/rhodonite = red, sphalerite = black and galena = grey.

perhaps the Ettlewood Calcsilicate representing the next-largest occurrence outside the orebodies. This observation has gone un-remarked by previous workers even though it shows that very unusual depositional conditions prevailed during the formation of 2L and similar orebodies. The percentage of calcite is variable throughout 2L (e.g. Hodgson, 1967; Maiden, 1972; Webster, 1994a) and was recognised to be "abnormally low" in the 2L section in the British Mine, thus raising the silver to lead ratio to higher than normal (Gustafson, 1939; Henderson, 1953).

#### 4.7.4.1. *Geometry of No 2 Lens.*

No 2 Lens is an elongate but convoluted mass of sulphides, calcite and various silicate species. It was originally up to 250 metres wide, lenticular in cross section and strongly layered. However, it is not a continuous zone of mineralisation throughout the central part of the mining field (northern South Mine to Block 14 Mine), where it is mostly absent. The main occurrence is as two preserved dismembered segments within a strongly attenuated synformal F2 fold keel occupying the southern side of the deposit. This has been dismembered by D3A shearing (refer to maps BHP2 to BHP5 in Appendix 1). The largest fragment of 2L is located towards the southwestern boundary of the former BHP Mine on ML11. 2L has not survived as well because it is thinner, possibly more ductile and it occupied a higher position than 3L. No significant 2L mineralisation lay above 3L in the central region of the field (see Chapter 6), which just reaches surface in the highest point above sea level that the deposit reaches (the ridgeline of the original 'broken hill').

In the South Mine, 2L becomes a distinct and continuous, well-defined, southwest plunging ore mass in its own right. It outlines well-preserved, relatively open to tight F2 fold geometries, the trend of which it transgresses at a low angle (Figure 4.25). The folded geometry of the orebody becomes attenuated near the Pasminco Mine lease boundary but redevelops at depth to the southwest. Below the 16 Level of the Pasminco Mine, the orebody becomes a gigantic, layered mass of ore, eclipsing 3L and developing a distinct layered character (e.g. Figure 4.20).

To the northeast of the British Mine, 2L becomes increasingly more significant as a relatively thin, but consistent, isoclinally folded and transposed 'ribbon' of ore that persists to depth in North Mine. The folded geometry of the orebody is markedly more attenuated and the orebody is more transposed than in the Pasminco Mine. The

variability in the geometry of 2L is best viewed by comparing the digital level maps presented in the Appendix 1 (refer to maps NTH3 to NTH30).

#### **4.7.4.2.     *No 2 Lens Contacts.***

The contact of 2L and wall rock metasediments is very sharp, even in the least deformed parts of the orebody on the underside of 2L in the at NBHC section of the Pasminco Mine (Webster, 1994a). This observation suggests that the contact between 2L and the wall rock psammites and psammopelite was very sharp prior to deformation and is not the result of the juxtaposition of mineralisation and wall rock during folding and shearing. Banding in both the metasediments and banded calcite ore in 2L is parallel to the contact in the least deformed areas.

In most parts of the mining field, 2L is in contact with clastic metasediments of the Lode Sequence. Only in the Pasminco Mine does the upper 2L contact abut against garnet quartzite and other lode rocks (e.g. Figure 4.11 and schematic in Figure 4.28a).

#### **4.7.4.3.     *Southwestern Termination of No 2 Lens.***

2L terminates in the Southwestern Region of the deposit, approximately midway through the Pasminco Mine, to the southwest of the NBHC Service and Haulage Shafts (Figure 4.14). Stopping, mine mapping, extensive exploration drilling and underground development have allowed detailed investigations to take place in and around the southwestern termination of 2L (e.g. McKay, 1974; Webster, 1994a). From this information it is apparent that 2L pinches out within a zone that is relatively weakly deformed, showing little evidence of folding or shearing. 2L ends in an apparently primary stratigraphic pinch out.

#### **4.7.4.4.     *Terminal Facies Changes in No 2 Lens.***

No 2 Lens undergoes several stratigraphic and mineralogical changes in the last several hundred metres of its southwestern strike extent. Important changes include the development of the 1 Lens orebodies as hangingwall branches of 2L (see section 4.7.5); the development of large rhodonite layers within the ore; the development of a clearly defined internal stratification within the orebody and a more complex interlayering with wall rock clastic metasediments. These important changes are

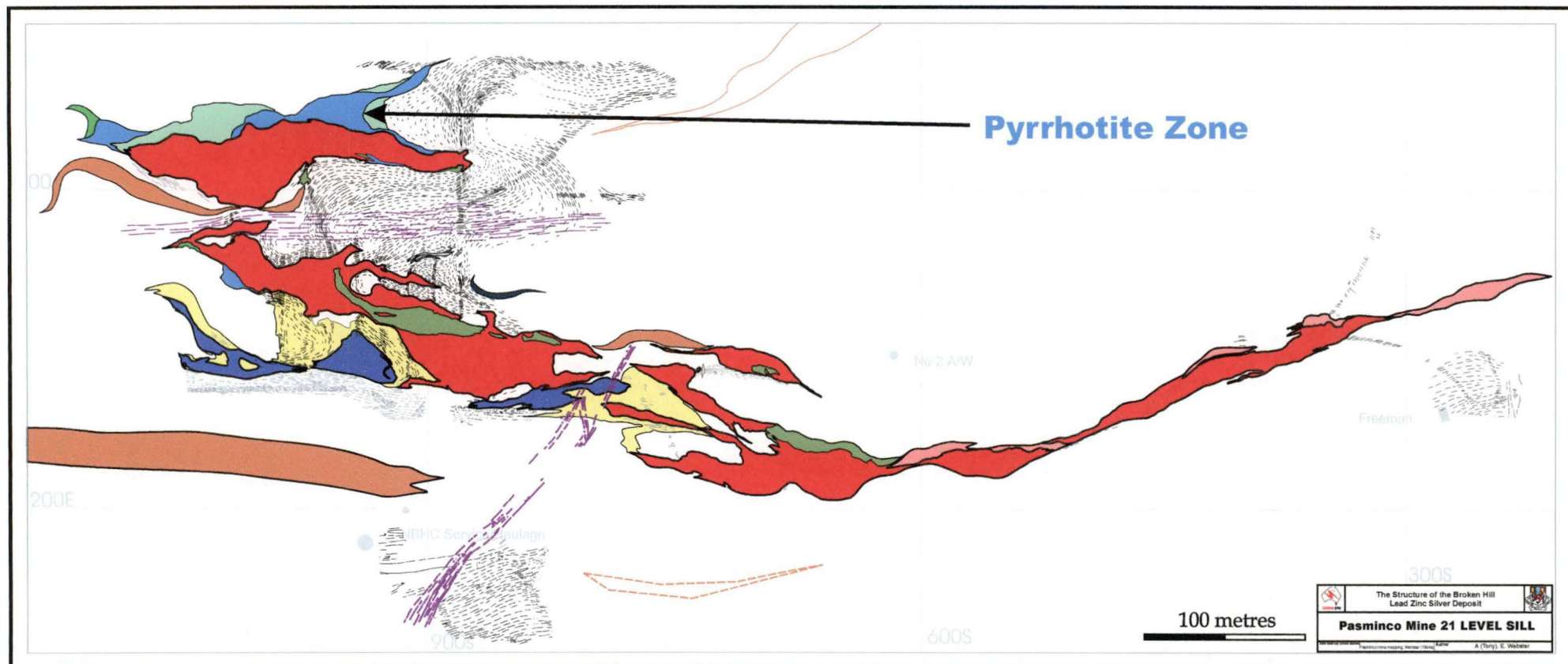


discussed in separate sections below (see section 4.7.4.8 to 4.7.4.11). The most obvious change is the development of a zone of mainly sub-ore grade to lead-zinc barren pyrrhotite that is often banded or massive. This zone was named the "Pyrrhotite Envelope" by McKay (1974) and is referred to as the 'pyrrhotite zone' in this thesis (Figure 4.32).

The pyrrhotite zone is most commonly a narrow, less than 2 metre-wide, contact zone of pyrrhotite or pyrrhotite-rich mineralisation that is a feature of the northern and northwestern contacts of 2L throughout the South (Figure 4.25) and Pasminco Mines. It extends from at least the 625 level of the South Mine to the final southwestern termination of 2L in the Pasminco Mine, between the 21 and 23 Levels. In the latter mine, around the 20 Level stopes, pyrrhotite forms a narrow 'rind', usually ranging in thickness from less than 5cm to 20cm (Webster, 1994a). Three metre-wide pyrrhotite lenses were also observed in 2L, occupying the contact between siliceous ore and calcitic ore (McKay, 1974). Siliceous ore is typically a hangingwall feature of 2L (northern and north-western side). One larger occurrence of pyrrhotite was also recorded on the Pasminco Mine 7 Level by Andrew (1922) who mapped an area of "highly pyritic ore" occupying the entire northern limb of 2L (map STH1170 in Appendix 1). The zone identified by Andrews (1922) is interpreted here as a part of the pyrrhotite zone.

A marked increase in the volume, geological and mineralogical complexity of the marginal pyrrhotite zone takes place at the southwestern margin of 2L in the Pasminco Mine. Here, a peripheral occurrence of weakly lead-zinc mineralised to barren, often banded pyrrhotite enshrouds the northwestern terminal margin of 2L (Figure 4.32). Immediately prior to the southwestern termination of 2L, between stope sections 16 and 32, the pyrrhotite margin dramatically increases in size to form a 250 metre long zone ranging in thickness from 5, to around 50 metres. This zone enshrouds the northwestern margin of the orebody (McKay, 1974). In this area, the pyrrhotite zone is a banded to massive body which is texturally similar to the adjacent banded high-grade 2L ore (Webster, 1994a). The pyrrhotite zone is variably enriched in calcite and chalcopryrite but also contains a variety of other minerals (Figure 4.33).

The pyrrhotite zone has sharp contacts with the sphalerite-galena-calcite ore of 2L but shows a continuity of calcite banding across the otherwise sharp contact. Carbonate banding within it is continuous with that in adjacent high-grade 2L ore. Webster



**Figure 4.32.** Plan of the 21 Level sill, Pasmenco Mine showing the location of the Pyrrhotite Zone on the northwest margin of 2L (sky blue). This is the largest development of pyrrhotite within the orebodies and has generally been considered by previous workers (e.g. McKay, 1974) to occur at the termination of the orebody. However, a narrow zone of pyrrhotite occurs in the same position on the northern margin of 2 Lens throughout the southwestern region of the mining field. Refer to the standard geological legend in the map folder.

(1993) observed that the contacts between the pyrrhotite zone and adjacent banded sphalerite-galena-silicate-carbonate mineralisation were sharp but that the carbonate banding within the ore was generally parallel to the pyrrhotite contact and with the carbonate banding in the pyrrhotite.

Detailed information about the geometry of the pyrrhotite zone is limited for much of its known strike extent (over 1.5 km), apart from basic information about its distribution in the South Mine, (Andrews, 1922) and the drilling-based description by McKay (1974). It has been accurately mapped in stopes and level development in the Pasminco Mine since McKay's (1974) work. The location of the zone is plotted on all South Mine and Pasminco Mine level plans, where information is available, and its distribution is interpreted in detail on the NBH21 Level geological plan; all of which are included in digital format in Appendix 1.

*Figure 4.33. Mineral constituents of the 2 Lens Pyrrhotite Zone.*

Location	Mineral Complement	Source
Pasminco Mine 21 Level	Alternating layers of pyrrhotite, calcite-pyrrhotite, quartz-pyrrhotite, & fluorite-pyrrhotite. Actinolite, calcite, quartz, garnet & rhodonite with rims of pyroxmangite. Dark hedenbergite rims on most small pyrrhotite lenses. Outer portions of pyrrhotite become more enriched in biotite towards contact with wall rocks. Massive accumulations of biotite occur up to 1.2m thick.	Hodgson (1967)
Pasminco Mine	Pyrrhotite, chalcopryite, sphalerite, galena, mackinawite, molybdenite, cubanite, marcasite, loellingite, arsenopyrite, Ni-Co-arsenides, magnetite, ilmenite, rutile, haematite, calcite, fluorite, biotite, garnet, hornblende, fluorite, muscovite, apatite, chlorite, rhodonite, bustamite, sphene, gahnite, epidote, zircon (?).	McKay (1974)
"Western Keel", 21 Level Pasminco Mine	2-4mm equigranular pyrrhotite, chalcopryite & varying proportions of sphalerite and galena. Calcite (most common gangue), usually interstitial to sulphides. Clear quartz common in matrix at the metasediment contacts. Can be massive or finely banded (defined by calcite & occasionally by chalcopryite-rich bands) . Galena & sphalerite are rare, except as veins at contacts with high-grade ore.	Webster (1994a)

Though the pyrrhotite zone is geometrically complex, because of deformation, it seems to have been a pre-D2 feature of 2L, because the banding and contact with high-grade ore has been folded by F2. It was probably originally stratiform, and although it could represent some form of early peripheral alteration of the primary lead-zinc ore, it is interpreted to be a terminal facies change within 2L (possibly an original stratigraphic unit).

Pyrrhotite-rich margins have been observed in other orebodies at BH. A narrow (probably less than 1 metre) occurrence of pyrrhotite occurs on the northern and



northwestern margin of 3L throughout the South Mine. This zone was recorded as being “pyritic” by the mining personnel who provided the information to Andrews (1922). Hudson (1994) recorded a pyrrhotite enriched northwest terminal margin in A Lode Upper in the Pasminco Mine.

#### **4.7.4.5.      *Northeastern Termination of No 2 Lens.***

The northeastern end of 2L, as currently defined, occurs at depth within the North Mine, where it is structurally offset by the Globe-Vauxhall Shear Zone below the 32 Level (Figure 4.14 and maps NTH30 to NTH40; especially NTH30 and 36, in Appendix 1). A small shear bounded block of 2L lies adjacent to 3L to the northeast of the GVSZ and forms a part of the Fitzpatrick Orebody (Leyh and Hinde 1990). 2L is not known beyond the Fitzpatrick area because it is sheared out against the Western Shear at depth, below the 36 Level, and no continuation has been located. However, northeast of the Western Shear, a fragment of BH mineralisation has been discovered and is known as the '2K' mineralisation (Leyh and Hinde, 1990). The '2K' mineralisation consists mainly of 3L (on the basis of gangue mineralogy), which is normally closely associated with 2L, as it is in the Fitzpatrick area. There is no reason why 2L should not extend into the '2K' zone, beyond the Western Shear. Extensions of the 2L orebody remain to be found in this region.

#### **4.7.4.6.      *No 2 Lens in the Central Region of the Mining Field.***

In the central region of the BH mining field, 2L is mostly restricted to dismembered segments preserved within a strongly attenuated synform keel that is located on the southern side of the deposit and best developed towards the southwestern boundary of ML 11 (Figure 4.14 and maps BHP2 to BHP5, in Appendix 1). The segment of 2L preserved within the keel forms a 'shoot' with an approximately vertical dip and southwesterly plunge. It outcrops as the “Eastern Lode” identified by Jaquet (1894) and which occurred on the southern side of the deposit between the southwestern end of ML 6 and between MacGregor’s and McBryde’s Shafts on ML 11 (Figures 4.1, 4.14 and Figure 5.1). Near-surface 2L ore was the main contributor of silver and lead to the rich “Dry High Grade Ore” (Jaquet, 1894) that outcropped on ML 11 (see Chapter 6).

2L also occurs as a thin sliver of mineralisation that persists throughout the southern margin of the Block 14 Mine, where it occurs within an attenuated fold keel (see maps

BHP1 to 3, in Appendix 1). Significant occurrences of 2L ore develop at depth in the British Mine. Despite the structural dislocations associated with the British Fault system, 2L remains remarkably consistent in size and geometry beyond the fault, and throughout its northeastern continuation in the North Mine.

#### 4.7.4.7. *Stratigraphic Associations of No 2 Lens.*

No 2 Lens lies within a relatively monotonous sequence of clastic metapsammites, metapelites and interbanded pelite and psammite. The 2L (and 3L) host rocks form a distinct unit within the underwall zone of the Mine Sequence. A stratigraphic package of closely associated, calcium enriched rocks lies immediately below 2 and is discussed further below. A schematic representation of the main features of 2 Lens is presented as Figure 4.28. Along-strike and up and down dip, 2L does not form a distinctive, recognisable stratigraphic horizon beyond its terminations. It pinches out sharply into normal clastic metasediments. No evidence has been found for 2L tapering off into a recognisable horizon southwest of its termination at NBHC (Webster, 1993) and this is the case elsewhere in the mining field. The orebody lenses out rapidly and abruptly into 'ordinary' psammites and psammopelites. 2L can be thought of as is an 'all or nothing' orebody, with no stratigraphic sign of its presence away from the main mineralised position. The stratigraphic position that 2L would occupy in the Mine Sequence will not have been tested in many cases if only the 'traditional' Mine Sequence has been drilled during exploration. Drilling the Mine Sequence package may only be testing the lode rock -rich position of the overlying orebodies (particularly BL), leaving the 2L (and 3L) position untested.

No 2 Lens had virtually no association with manganiferous garnet quartzite lode rocks, (unlike the overlying orebodies), only rarely being in contact with them in some areas on the upper contact. This orebody is almost completely encompassed by a monotonous sequence of interbanded medium to dark-grey psammites and psammopelites. It is only in the southwestern part of the orebodies, where the 1 Lens orebodies develop, that the Garnet Quartzite Horizon projects downwards into the clastic metasediments hosting 2L. In this region, below the Pasminco Mine 18 Level Sill, 2L is in contact with the GQH on its hangingwall side.

Closely associated with 2L is the underwall zone of the Footwall Sequence, described above (section 4.3.6, Figure 4.9). This part of the Mine Sequence contains calcium-

enriched lithologies such as calc-silicate horizons, amphibolites and the underwall Potosi gneiss units.

BIF layers are also present within the underwall zone of Footwall sequence, as well as elsewhere in the Mine Sequence. Several earlier workers have considered the BIF units to represent the along strike position of the "lead lodes" and/or the "zinc lodes" (e.g. Johnson and Klingner, 1976). BIF occurrences that are mapped to the northeast and southwest of the main orebodies, and which are defined at depth by drilling, remain separate from the main orebody position, and form distinct horizons throughout the mining field. BIF units occur throughout the near-ore Mine Sequence, both in the footwall (underwall zone of the Footwall Succession) and in the hangingwall (at the top of the Mine Sequence, near top of the Broken Hill Group). BIF units are probably associated with the mineralising system, but they are not the direct, along-strike equivalents of 2L or 3L.

The B Lode Horizons that overlies 2L forms an extensive and easily recognised marker horizon beyond the main ore grade occurrences of the mining field. This unit marks the mineralised position on a district scale. While it is considered that 2L does not form a significant stratigraphic horizon beyond the main mass of the mineralisation, the calc-silicate-rich psammite/psammopelite position that is often seen below 2L in the Footwall Succession is considered to be a guide to the approximate position of 2L within the distal parts of the Mine Sequence.

In the Pasminco Mine, 2L contains one or more mostly un-mineralised manganiferous horizon within the main mass of the mineralisation. It also contains many fine bands and laminae of manganiferous minerals within the body of the ore (rhodonite and bustamite-rich bands within calcitic ore). This aspect of the stratigraphy of 2L is more fully discussed below.

#### **4.7.4.8.      *Internal Stratification of 2 Lens.***

A primary stratification of 2L was recognised by Webster (1993; 1994a) who showed, through the identification of distinctive styles of mineralisation and mapping their distribution, that 2L is a stratified body, which is conformable with the surrounding Mine Sequence stratigraphy. He recognised three main categories of mineralisation forming 2L;

- Stratiform mineralisation,
- Mobilised mineralisation and
- Metasomatically altered mineralisation.

The latter two ore type categories are syn-tectonic while the former types are interpreted by Webster (1993; 1994a) to be primary layered features of the orebody. This interpretation has been supported by the current study and the bulk of 2L is now seen to be comprised of four main types of stratiform mineralisation (Figure 4.34; Figure 4.35 and 4.36), which are;

1. A lead-zinc sulphide rich upper contact zone (massive equigranular sulphides).
2. A Pb-Zn-Ag rich calcium-carbonate rock, which was banded by layers rich in sulphides and layers rich in calcite. Minor laminae of silicate-manganese minerals are common in places and develop into significant bands up to a metre or so in thickness; fluorite-defined zones and apatite-rich layers are common in places.
3. A Pb-Zn depleted or barren, manganese-silica bearing layer, probably lenticular in form, which was interlayered with the banded sulphide-rich carbonate rock and were interbanded with the carbonate.
4. An iron-rich sulphide phase located on the southwestern margin, which is now the pyrrhotite zone described above.

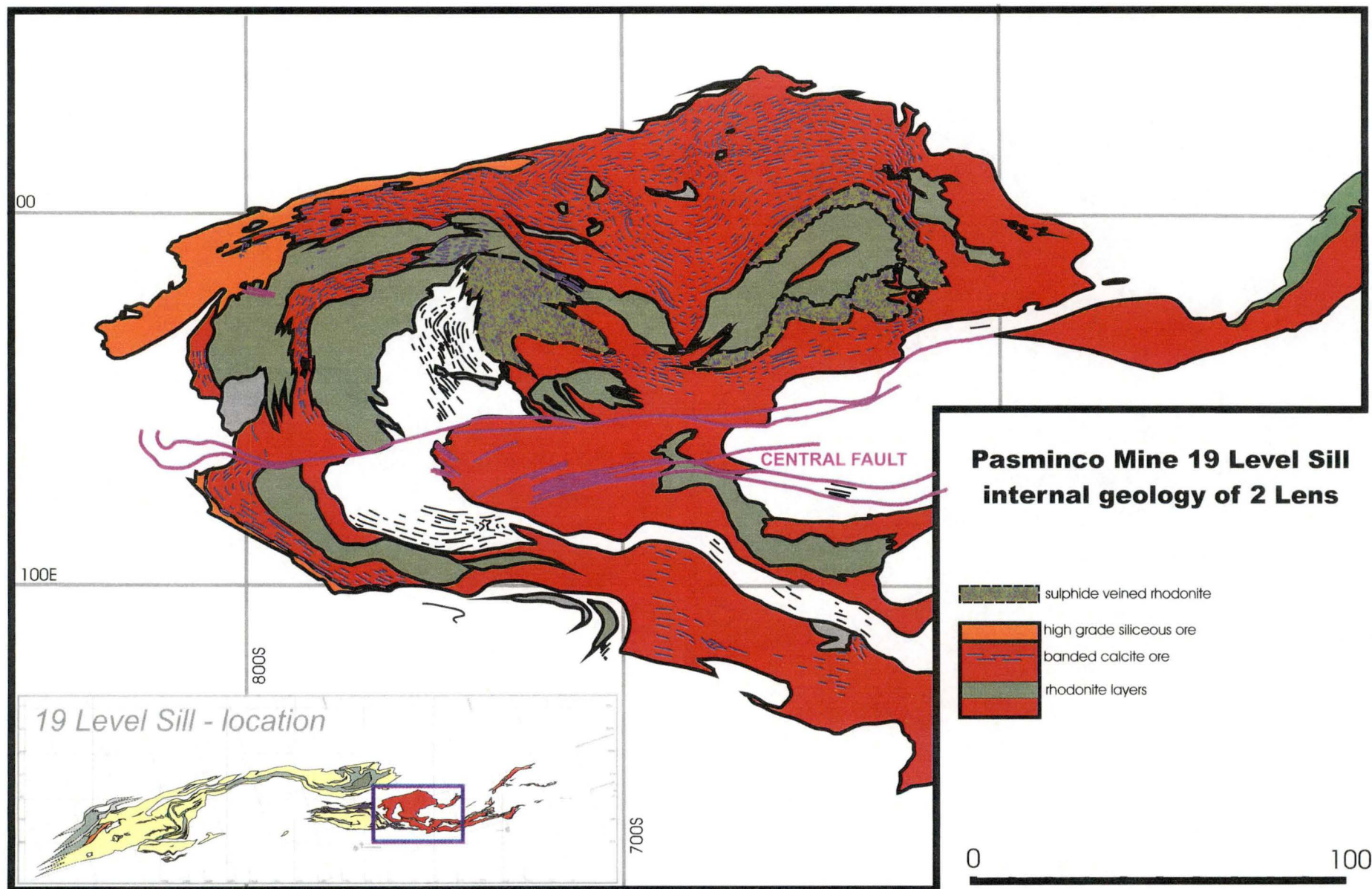
These features are discussed in detail in the following sections.

The recognition of a pre-tectonic stratification in 2L was one of the most important results of the work of Webster (1994a) and it has provided one of the foundations for the current study. As a result, primary stratification has now been recognised in most of the significant orebodies of the BHI deposit (including 3L, B Lode, 1 Lens Upper and A Lode Lower).

Figure 4.34. Primary zones within No 2 Lens (see Figures 4.35 and 4.36).

Zone	Where known	Description
<b>Sulphide-Quartz Zone</b>	<ul style="list-style-type: none"> <li>• South Mine</li> <li>• Pasminco Mine, upper contact of 2L, below 16 Level sill.</li> </ul>	A sulphide-rich zone with minor quartz as clasts & as disseminated zones forms the upper part of 2L (the Massive Equigranular ore of Webster, 1994a). A similar zone is present in 1 Lens Upper between the 19 & 20 Level and probably in 1 Lens Lower. This 2L zone is comparable to the quartz-rich upper zone in 3L & to high grade B Lode ore.
<b>Fluorite Zone</b>	<ul style="list-style-type: none"> <li>• Pasminco Mine (between 19 &amp; 21 Levels of the NBHC area)</li> </ul>	<p>A fluorite-calcite rich zone within calcitic ore. Contains abundant bluish-green apatite. Webster (1994a) observed this zone to consist of granular, pale, translucent orange-pink, equigranular 2-4mm fluorite crystals (up to 60% of the rock) within a white calcite matrix or with calcite as an interstitial component. Galena, sphalerite, +/- chalcopyrite, loellingite (in places) &amp; traces of pyrrhotite occurred as interstitial grains, particularly at triple-junction points of the larger fluorite crystals. Fluorite-rich ore was often banded in a similar manner to the calcitic ore, except that fluorite was the main component of the banding. Observed to form discrete 0.5 metre-wide bands within calcitic ore.</p> <p>Gustafson et al (1950) observed a local occurrence of conspicuous pink fluorite crystals on the 18 Level at NBHC enclosed in calcite. They also noted that in places 2L fluorite was green or white, &amp; rarely red or brown fluorite.</p>
<b>Banded Calcite Ore Zone</b>	<ul style="list-style-type: none"> <li>• The major ore type of 2L. Present in all parts of the orebody, from the North to Pasminco Mines.</li> </ul>	Banded calcite-sulphide-silicate rock forming the bulk of 2L throughout the mining field.
<b>Rhodonite Zone</b>	<ul style="list-style-type: none"> <li>• Pasminco Mine below 16 Level sill</li> </ul>	<p>In the Pasminco Mine, a Pb-Zn depleted or barren, manganese-silica bearing layer, probably originally lenticular in form, is interlayered with banded sulphide-rich calcitic ore. This zone is usually massive in 2L but bands &amp; layers of calcite-bustamite-rich calcite ore are also present. The Massive Manganese Silicate Mineralisation of Webster (1994a).</p> <p>Gustafson et al (1950) noted that rhodonite develops in 2L below the 12 Level at NBHC. In the nose of the "Western Anticline" significant wollastonite &amp; hedenbergite were seen associated with rhodonite. They considered 2L rhodonite to resemble 3L rhodonite in the British Mine area.</p>
<b>Pyrrhotite Zone</b>	<ul style="list-style-type: none"> <li>• Northern &amp; northwestern margins of 2L in South &amp; Pasminco Mines. The major occurrence is between the 20 &amp; 22 Levels.</li> </ul>	See text

Prior to deformation, and large-scale sulphide mobilisation, lead-zinc mineralisation was not present within the massive rhodonite zones (or their precursors) in 2L. Nor were sulphides present within the other mangiferous rocks associated with the BH orebodies, such as garnet quartzite and garnet sandstone. Lead-zinc-silver sulphide mineralisation lying above 2L was restricted to discrete siliceous and/or calcareous



**Figure 4.35.** Detailed geological plan of the 19 Level sill of the Pasminco Mine (NBHC area) showing the internal stratigraphy (S0) of 2 Lens. The orebody has three distinct zones within it that are defined by gangue mineralogy, sulphide density, fabrics within the sulphide-silicate-carbonate rocks. For legend, refer to standard geological legend. The inset shows the position of the main figure relative to the geology of the entire mine level. Refer to Figures 4.35 and 4.36 which also depict 2 Lens in this area.

layers, which were hosted within manganiferous rocks but the manganiferous rocks do not appear to have been originally mineralised.

Quartz is only present at the margins of 2L as veining and as a minor gangue constituent. This observation suggests that it has only been introduced into marginal areas as a component of the mobilised styles of mineralisation.

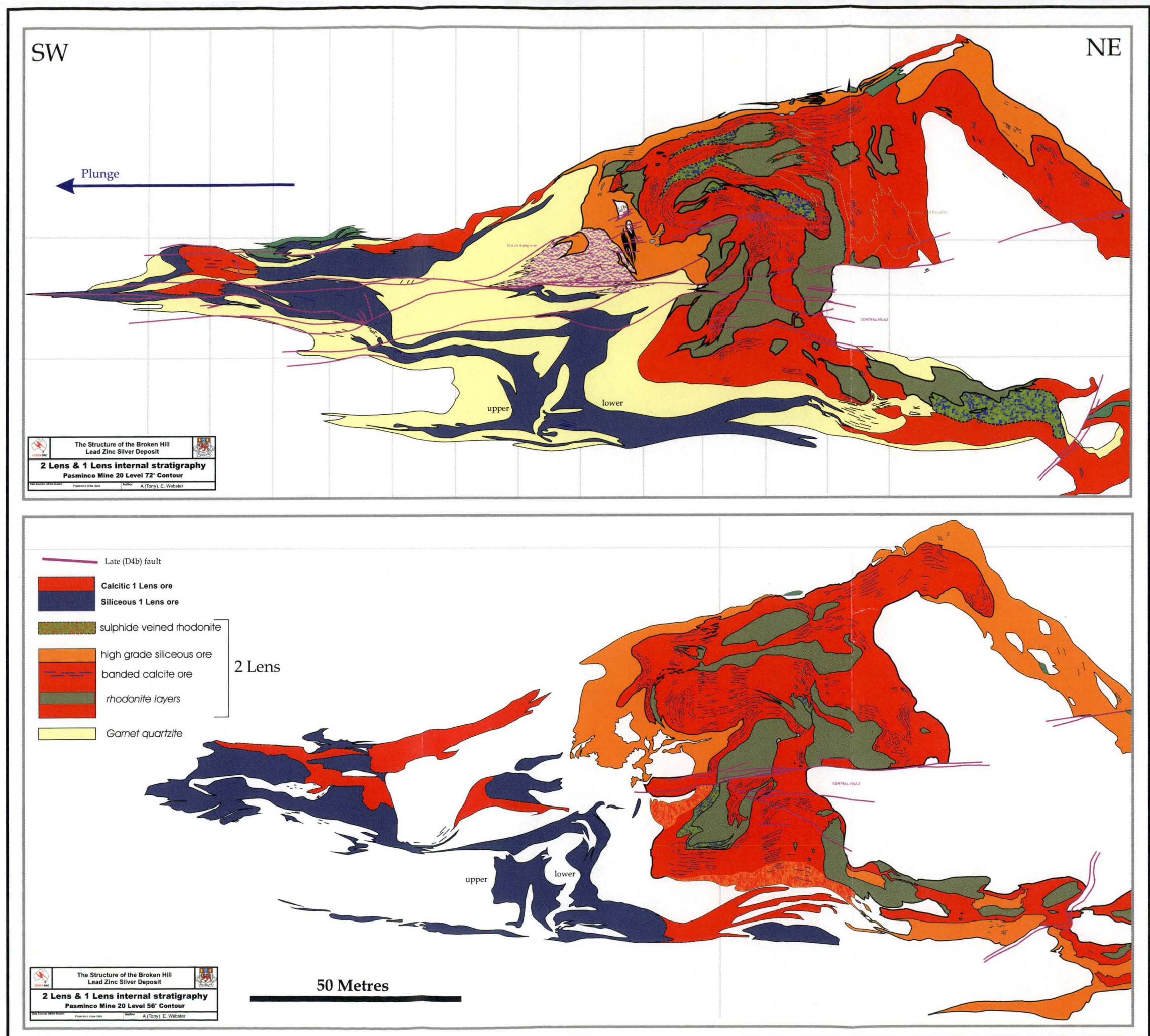
Lode pegmatite is a local name for a medium to coarse-grained quartzofeldspathic rock composed of K-feldspar, plagioclase and quartz with minor garnet and biotite. They commonly contain irregular patches of green or grey lead-bearing orthoclase. They have a close spatial association with the ore lenses (Haydon and McConachy, 1987). Pegmatites that have intruded 2L are particularly focussed along the upper contact of the orebody where they are dismembered by plastic flow within the ore. Although deformed in this way, patches pods and clots of pegmatite have been traced by mapping and still define distinct layers and bands. Individual pegmatite bands have been traced for tens of metres within 2L and have been successfully used as marker bands to define the geometry of F2 folds within the mineralisation (Webster, 1994a). Pods of pegmatite are often rimmed and impregnated with D2 wollastonite and most green feldspar only survives as cores within larger individual crystals due to alteration during D2 (Webster, 1993; 1994a).

#### 4.7.4.9. *Massive Rhodonite Zone*

Distinctive zones of rhodonite were identified in 2L in the Pasminco Mine by several workers (e.g. Hodgson, 1967, Maiden 1972) but Webster (1993; 1994a) interpreted such zones to represent from one to three closely associated early layers in the orebody. This mineralisation occurs as large ragged masses, particularly below the 16 Level, becoming more extensive from northeast to southwest and possibly mirroring the development of the overlying Garnet Quartzite Horizon. Further work has confirmed this observation in 2L and similar layers have been recorded in other parts of the deposit, including 3L (Figure 4.20, 4.35 and 4.36; see also maps NBH15 to NBH21 in Appendix 1).

The distribution of the massive rhodonite in 2L is very layer-like and is best explained by an origin as a single stratiform layer (or possibly 2 to 3 layers) that has been boudinaged on a large scale during deformation. Fold hinges are preserved by some





**Figure 4.36 a and b.** Geological plans of successive stope lifts above the 20 Level. These plans illustrate the consistency in the internal stratification (S0) of 2 Lens in the Pasmaico Mine. 1 Lens Lower is also stratified in this region of the mine, comprising an upper sulphide-rich siliceous zone and a lower banded calcite zone that is also strongly layered where it reaches its greatest development. Also refer to Figures 4.37 and 4.35 which also depict 2 Lens in this area.

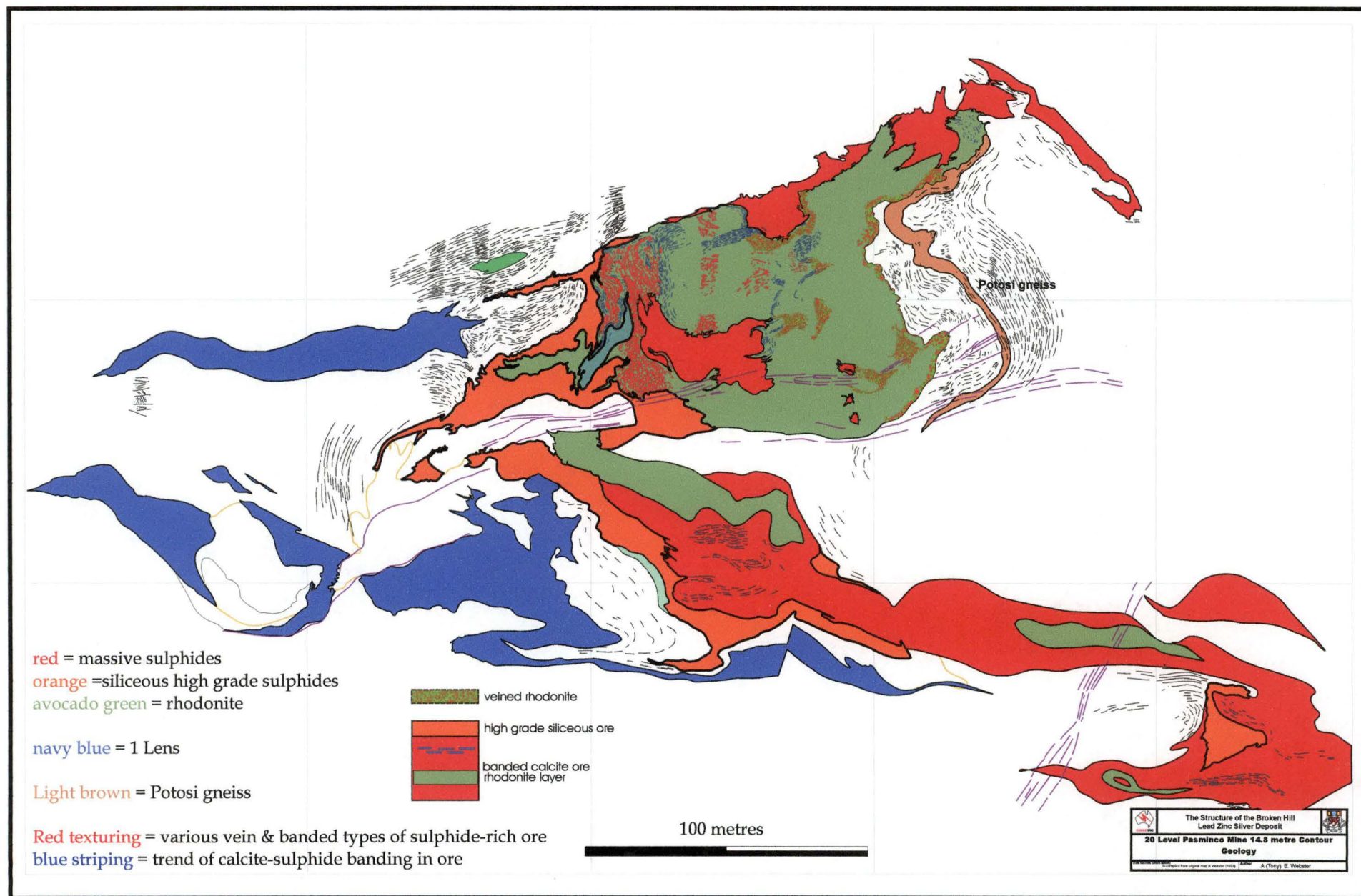


of the larger manganese silicate masses and are preserved as tight F2 fold hinges developed within the rhodonitic layer. The fold hinges were dismembered later in D2 and now 'float' in the surrounding banded calcite ore. The layered form of this style of mineralisation in 2L was therefore present prior to F2 folding, supporting the view of Burrell (1942) who interpreted similar layers in 3L to be a primary feature. The formation of separate, ragged masses from the original layer is interpreted to have occurred because of the higher relative competency of the manganese silicate compared to the more ductile, banded calcite ore (Webster, 1993; 1994a).

The centres of rhodonite masses are very low grade and texturally distinct from the margins, being medium to coarse-grained and equigranular in texture. This texture is interpreted to reflect an early recrystallisation phase of the original rhodonite layer (Webster, 1994a). The texture preserved in the centres of large masses is distinct from the coarsely recrystallised and sulphide-veined margins. Bustamite and hedenbergite are also common as coarsely crystallised phases that are intimately intergrown with mobilised sulphides along the outer edges of rhodonite masses. The textural relationship between the coarse mobilised sulphides, which occur as veins, and the coarsely re-crystallised rhodonite and calc-silicates on the margins of weakly mineralised and equigranular rhodonite suggests that mobile sulphides 'mineralised' the margins of rhodonite masses during deformation at high metamorphic grade. Therefore, the deformation of the original layer occurred prior to, or during granulite facies metamorphism (Webster, 1993; 1994a).

Layers of banded calcite ore from 2 to 5 metres wide are preserved within the centre of one of the rhodonite masses on the 20 Level of the Pasminco Mine (Figure 4.37). These small layers define the axial surfaces of F2 folds in the ore and preserve the distortion of these early folds by D3 shearing. Metamorphic differentiation on a large enough scale to form such large and uniform masses of rhodonite would be unlikely to form such unevenly distributed, finely banded layers of carbonate mineralisation. Fine layers of banded calcite ore within massive equigranular rhodonite are interpreted to be evidence that the rhodonite layers were deposited contemporaneously with the calcite ore (Webster, 1993, 1994a).

Some previous workers have interpreted the large masses of manganese silicate to be an early inhomogeneity within the mineralisation (e.g. Maiden, 1972; Hodgson, 1967) suggested that manganese silicate masses represent infolded masses of wall rock



**Figure 4.37.** Geological plan of the 14.8 metre contour of the 20 Level, Pasminco Mine, showing the internal stratigraphy of 2L. Refer to Figures 4.36 and 4.35 which also depict 2 Lens in this area. 1 Lens is also shown (navy blue). Modified after Webster (1994a).

metasediments that have been intensely altered. This is considered unlikely by the writer because the style and intensity of visible folding is not consistent with the process, and there is no evidence of this manganese enrichment of the true wall rocks.

The formation of the manganese-rich precursor of the rhodonite layers in 2L may be genetically linked to the process that formed the nearby manganese-rich Garnet Quartzite Horizon. Both rock-types are rich in manganese and silica, are barren of base metals, have a layered distribution throughout the deposit and have a similar geographic distribution through the deposit.

#### ***4.7.4.10. Sulphide-Silicate-Calcite Banding.***

A strong sulphide-silicate-calcite defined banding is present within the calcitic ore that forms the bulk of 2L throughout the mining field. It was described in the Pasminco Mine by Hodgson, (1967), Maiden, (1972) and Webster, (1993; 1994a) (Figure 4.31a, b, c, e). The banding is overprinted by a variety of syntectonic fabrics represented by textural and mineralogical variations in the ore. The banding is concordant with the least deformed contacts of 2L and parallels the metasedimentary banding of the immediate wall rocks in most areas, such as the underside of 2L in the Pasminco Mine. The banding is transposed where the orebody is intensely folded along with the enclosing metasediments, as is the case in the North Mine (Figure 4.24).

Webster (1993; 1994a) showed that the sulphide-silicate-calcite banding is parallel to the upper and lower contacts of 2L and was folded in concert with the surrounding metasediments (Figures 4.35-4.37). The remaining layered form of the rhodonite masses in 2L lies approximately parallel to the banding. Calcitic ore is enriched in sulphides relative to calcite within zones that lie adjacent to the rhodonite masses. This enrichment is interpreted to be the result of sulphide mobilisation and re-deposition during first generation folding. A discrete stratigraphic layer of fluorite-carbonate mineralisation has been mapped by Webster (1994a) in 2 Lens on the 20 Level at NBHC (the "Fluorite Zone" mentioned in Figure 4.30).

Sulphide-silicate-calcite banding predates the large-scale boudinage of the rhodonite layers and is intensely distorted or truncated at the contacts. Mineralisation with a diverse range of calc-silicate minerals developed at the interface between these masses and the banded calcite ore (the mineral assemblages that developed are dominated by

pyroxenes and pyroxenoids, suggesting granulite facies). The banded texture was preserved as a ghosting within the sulphide-enriched material however (Webster, 1994a). The banding cannot be a product of plastic flow, formed during high-grade metamorphism (as suggested by Maiden, 1972) unless this occurred on a large scale prior to the development of the F2 folds, widespread sulphide mobilisation and prior to the peak of regional metamorphism (Webster, 1994a). If the sulphide-silicate-calcite banding developed from the metamorphic differentiation of sulphides and carbonate (as Hodgson, 1967 has suggested), this process would have had to have occurred before granulite grade metamorphism and prior to the two main deformations which have affected the mine area (F2 folding and D3 shearing). Deformation that was severe enough to produce such pervasive plastic flow would have been associated with the extensive sulphide mobilisation and intense textural modification of the orebody. No such features predate F2 folding (Webster, 1994a).

Condon (1959) concluded that carbonate banding represented bedding and identified sedimentary structures within it. The preservation of true sedimentary structures in the ore, other than bedding, is considered unlikely by the writer, at least in Condon's localities, because they occur in the most intensely attenuated and deformed marginal areas of the orebody. However, the banded fabric is considered a primary feature of the orebody (S0). It is interpreted to be a depositional layering formed during the primary accumulation of the sulphides. It has been coarsened and extensively modified by metamorphism, sulphide mobilisation and deformation (Webster, 1994a).

#### *4.7.4.11. Massive Sulphide-Quartz Zones in No 2 Lens.*

A massive sulphide, +/- quartz zone was identified on the upper margin of 2L in the Pasminco Mine by Webster (1993; 1994a) (his "Massive Equigranular Sulphide Dominated Mineralisation"). At the time, this was interpreted to be a syntectonic, mobilised style of mineralisation. However, the distribution of the zone has been defined more completely (Figures 4.35 to 4.37) and it has been recognised in 2L in the South Mine (Figure 4.25). Comparable zones have also been identified in other orebodies (e.g. 1 Lens Upper and 3L). The textures and geological relationships of the zone within 2L in the Pasminco Mine have also been re-evaluated and this information suggests that it is a primary quartz style of mineralisation (akin to 3L and BL), which formed as part of the original deposition of 2L.

There are several small pieces of evidence for a primary origin of the massive sulphide-quartz zone in 2L. The first is that narrow bands of green feldspar lode pegmatite are preferentially emplaced along the contact between the massive sulphide zone and banded calcite ore (Webster, 1994a). These small dykes are folded by F2, dismembered, and altered by the same D2 event. Webster (1994a) considered the massive sulphide-quartz zone to have formed during D2, but this relationship is more consistent with a pre-D2 origin. The second piece of evidence is that this layered zone has concordant contacts with the banded calcitic ore in 2L. Thirdly, this style of mineralisation occurs as similar layered zones in 3L, in both the Pasminco and North Mines, and it is present as layered zones in all of the other orebodies of the deposit (e.g. 1LL, 1LU), particularly as a feature of the upper contact. It is also the predominant ore type in BL, where it is strongly banded. All such zones are folded by F2.

#### **4.7.5. The 1 Lens Group (1 Lens Upper and 1 Lens Lower).**

The 1 Lens Group comprises two (possibly three) zinc-rich layers of very high-grade mineralisation within a predominantly calcite-quartz gangue. They are known as 1 Lens Upper (1LU) and 1 Lens Lower (1LL) respectively and occupy positions between the upper contact of 2 Lens and the footwall of A Lode Lower and the lower contact of the Garnet Quartzite Horizon. A third 1 Lens style mineralised horizon is being developed near the 16 Level of the Pasminco Mine. The 1 Lens Group is only known within the Pasminco Mine. The lode identified as "1 lens" in the upper levels (above the 13 Level) of the Pasminco and South Mines by Gustafson (1939) and Gustafson (1950) is interpreted here to be B Lode. The twin orebodies reach their most significant dimensions between the 11 and 22 Levels of the Pasminco mine and reach their greatest thickness from the 17 to the 21 levels. They taper off up-plunge to the northeast and down-plunge to the southwest.

The orebodies were mostly mined out by the early 1990's, leaving only small, lower grade remnant blocks and pillars. The close proximity and structural complexity of the ore lenses has resulted in their frequently being mined together, particularly along the southern margins of the NBHC section of the Pasminco Mine. Between 1979 and 1983, the 1 Lens orebodies produced at an average mining grade of 9.6% Pb, 53g/t Ag and 22.4% Zn (Haydon & McConachy, 1987). Up to 1987, the 1 Lens orebodies produced an estimated total of 5,095,277 tonnes of ore (Burton, 1990). The remaining mineable

tonnages, >3% combined lead and zinc, remaining in 1 Lens in 1996 is shown in Figure 4.38. This should not be considered an accurate reflection of the overall grade of these orebodies. The remnant pillar resource estimated in the same year was; 350,535t @ 8.4% Pb, 65g/t Ag and 21.2% Zn. Between 1979-83, the actual mining grades of the 1 Lens orebodies was 9.6% Pb, 53 g/t Ag and 22.4% Zn. The latter figures are probably a more accurate reflection of the original grade of these orebodies.

**Figure 4.38.** *Remaining resource in 1 Lens, Pasminco Mine. (Pasminco Mining, unpublished data).*

	tonnes	Pb%	Ag g/t	Zn%
<b>Measured</b>	287,032	3.7	40	4.4
	892,727	2.1	26	2.6
<b>Indicated</b>	188,376	3.0	39	5.0
	867,866	2.2	27	2.5
<b>Inferred</b>	42,322	2.5	43	5.1
	181,575	1.7	42	3.3

1 Lens Lower has a similar gangue mineral complement to 2L, being calcite-rich in places, particularly along the lower margin. As in 2L, the distribution of gangue species is not random but defines a distinct zonation in the orebodies (see Figure 4.36a & b). This is particularly evident in 1LL where well-defined layered zones of high-grade siliceous and high-grade calcitic ore (footwall) are present. Stratification is best developed where the orebodies are thickest, such as between the 19 and 20 Levels (Figures 4.36). Low grade banded quartz-wollastonite ore was observed in the 10E Stope on the 20 Level of the Pasminco Mine (Maiden, 1972).

1LU is generally siliceous and probably does not have a well-developed calcitic layer. Apart from calcite and quartz, gangue species identified within the 1 Lens orebodies include wollastonite, bustamite, hedenbergite and epidote (Haydon & McConachy, 1987). Gustafson et al (1950) noted fluorite in the "Overwall Zinc Lode" between 2L and the Rhodonitic Zinc Lode (A Lode Lower). This probably refers to 1L. There is an increase in pyrrhotite and garnet content at the extremities (McKay, 1974) and small developments of pyrrhotitic lode rocks develop around the southwestern terminations of both 1LU and 1LL (Haydon & McConachy, 1987).

Banding, defined by variations in sulphide and gangue mineral (quartz and calcite) density, is well developed in all ore types within the 1 Lens Group, being equally well developed in both the calcitic and siliceous ore types.



Strong metasomatic alteration of the primary ore at the lens terminations is seen along the southern margin of both 1L orebodies and has formed distinct siliceous-sulphide veining associated with silicified-blue quartz, clear and white quartz veining (Hodgson, 1968; Webster, 1993). Particularly well-exposed examples were mapped on the 20 Level, 14.8 metre contour, near the NBHC Service Shaft (Webster, 1993; 1994a)

The lithological associations of the 1 Lens Group differ from the overlying A Lode and B Lode orebodies and are very similar to 2L (see below). 1 Lens Upper and Lower are hosted within psammitic, psammopelitic and pelitic metasediments (Haydon & McConachy, 1987) for a large part of their strike length, having only a weak association with garnet quartzite. However, below the 18 Level, they converge with the Garnet Quartzite Horizon (GQH), initially along their eastern margins. They remain largely separate from the main body of the GQH until just above the 19 Level. 1 Lens Lower and Upper both increases in thickness down plunge as they merge with the with the footwall of the GQH but they are never fully contained within it. In the same plunge interval, the eastern development of A Lode mineralisation dies out. Cordierite-rich garnet quartzite envelops parts of the 1L orebodies (Billington, 1979).

1 Lens Lower pinches out on the northwestern side into a large body of garnet sandstone on the 20 Level. This body of sandstone was examined in some detail, both within the "Pig" Loader Cut and Fill Stope, and in exposures on the 20 Level sill (Figure 4.13). As is discussed elsewhere (section 4.4.2.3 and see Figure 4.12), garnet sandstone is considered a metasomatically altered form of garnet quartzite.

The 1 Lens orebodies have traditionally been classified as "Zinc Lodes", mainly based on their high zinc to lead ratio. In fact, their geology most strongly resembles 2L and they are very lead rich compared to the other "Zinc Lodes" despite their elevated zinc content. 1LU and 1LL are geologically distinct from AL and BL because they possess many geological features in common with 2L. Similarities include a calcite gangue, well-developed internal stratification and a clastic metasedimentary host sequence. The 1L orebodies do not tail off into a recognisable marker horizon as do BL and AL and they are largely separate from the Garnet Quartzite Horizon.

#### 4.7.5.1. *Southern 1 Lens.*

The geology of this region of the Pasminco Mine has not been investigated in detail because it was the focus of intensive mine geological investigation and a Masters thesis study (A. Morley) at the time the present project commenced. It has not been investigated in detail and so only general comments are made.

Southern 1 Lens (S1L) is a separate mineralised zone in the Garnet Quartzite Horizon that consists of up to three high-grade, stacked ore lenses up to 20m wide (Mackenzie & Davies, 1990; A. Morley and J. Murray pers. comm. 2000). It is developed in the footwall of B Lode in the Southern Cross region of the Pasminco Mine (southwestern end of mined area) and lies to the south of Southern A Lode (see section 4.7.8). It is separated from SAL by 80-100m of garnet quartzite (Mackenzie & Davies, 1990). S1L was initially interpreted to be an additional lens of SAL but the thick interval between this zone and S1L, and its similar metal ratios and gangue mineral complement to 1L, led mine geologists to interpret the zone as a remake of 1 Lens. It has a quartz, garnet, +/-bustamite gangue (Mackenzie & Davies, 1990).

S1L occurs in the same approximate stratigraphic position as the 1 Lens Group (relative to BL and SAL), though separated from these orebodies by over 500m. It is contained within a tight, complexly sheared synformal F2 fold (the Southern Cross Synform) that is partly shear-bounded (see maps NBH 20 and NBH21, in Appendix 1). Despite the suggested similarities to the main 1 Lens orebodies, the stratigraphic affinities of this zone are uncertain. The bustamite gangue does suggest an affinity with the 1L Group (and even 2L) however, and it could represent a separate development of a slightly more calcic ore zone in the equivalent stratigraphic position to these orebodies. Erosion in the Palaeoproterozoic ocean may have removed the intervening zone between, 1LL/1LU or 2L, leaving this orebody as a remnant.

#### 4.7.5.2. *The Relationship between 1 Lens Lower, 1 Lens Upper and 2 Lens.*

The 1L orebodies originate as branches of 2L and diverge from the main orebody between the 17 and 18 Levels of the Pasminco Mine (Figure 4.20). The region of 2L between the 16 and 19 Levels of the Pasminco Mine is marked by an increased stratigraphic complexity within the mineralised horizon, as well as a significant increase in thickness, ore tonnage and mineralogical diversity. 2L is divided into a

series of layers and these are interdigitated with tongues of clastic metasediments. By the 18L sill, peninsulas of metasediments develop in the northeast and southwest end and in between the tongues of metasediment; a large mass of manganese silicate rock is developed. The manganese silicate comes to dominate the geology of the orebody in this area. High-grade banded calcitic ore is split into two distinct layers by the manganese silicate and tongues of metasediment to form a hangingwall layer and a footwall layer (Figure 4.20, reconstruction). It is in this region of 2L that the 1 lens orebodies become prominent features of the Lode Horizon and branch off the main body of 2L (Figure 4.20, see also map NBH18 in Appendix 1). Where 1LL diverges from 2L, there is a corresponding development of the sulphide-quartz zone in the upper part of 2L.

High-grade calcitic ore is draped over the hangingwall and footwall and protrudes for several tens of metres beyond the rhodonite mass that forms the core of 2L. On the 18L sill the hangingwall 'tongue' of 2L banded calcite ore projects approximately 70 metres to the southwest of the rhodonite mass (Figure 4.20). The hangingwall 'tongue' resembles the geology of the 1L orebodies and could almost be a third development of these ore lenses. It is also possible that 1LL, at least, is geologically contiguous with 2L on the 17L sill (Figure 4.20). While it is possible that this is due to structural juxtaposition, it is possible that the contact is an early stratigraphic feature of the orebodies. They may be in contact. Therefore, apart from the physical connection, there is a possible direct geological relationship between 2L and the 1L orebodies.

Structural dislocation has removed the direct contact but has not destroyed the stratigraphic complexity of the 2L layering. The main rhodonite masses in 2L also reach their best development in this region of increased complexity. While the rhodonite is not considered to be altered metasediments, it shows a direct spatial relationship with the development of the zone of stratigraphic complexity in 2L.

The region of the mining field between the 16 and 19 Levels of the Pasminco Mine is also the zone where 3L diminishes and largely disappears, probably dying out and developing a zone of 2L-like mineralisation on its southwestern margin (Figure 4.20, 4.28b).

It is suggested that Upper and Lower 1 Lens can be thought of as continuations of the 2L mineralised system but represent transitional phase between 2L calcite-dominated

ore styles and the siliceous "Zinc Lode" dominated orebodies of the upper part of the deposit.

#### 4.7.6. A Lode Lower.

The A Lode mineralised horizons have been recognised as a zone of economic importance since the late 1940's, being recognised as the "Rhodonitic Zinc Lode" by Gustafson et al., (1950) and King and O'Driscoll (1953). Exploration and mine development drilling in the 1960's resolved the horizon into two separate mineable bodies; A Lode Upper (ALU) and the underlying A Lode Lower (ALL). ALL lies between ALU and 1 Lens Upper, at a characteristic stratigraphic position on the lower contact of the Garnet Quartzite Horizon. Both ALL and ALU have similar wall rock associations and are tectonically modified in many areas, often to the extent that the two zones become indistinguishable. Therefore, they have generally been classified together for resource definition purposes, particularly in parts of the mine where their resolution is less clear (e.g. Haydon & McConachy, 1987). Specific tonnage and grade figures for ALL cannot be easily resolved. Figure 4.39 provides a summary of resource grades.

In general, ALL is an ore lens that consists of a core of high to medium grade sulphide mineralisation, often with an associated rhodonite layer and is usually hosted within a halo or zone of siliceous blue quartz rocks that are interpreted to be a syntectonic alteration that was mainly formed during D2/D3A. There is a persistent rhodonite zone within the unit that is up to 30 metres thick (as on the 14 Level) and which occurs throughout the strike length of the orebody. Simplistically, it can be regarded as being roughly lenticular in cross section but is elongate. Significant mineralisation is best developed where the rhodonite zone is most conspicuous.

*Figure 4.39. Tonnes & grade of "A Lode" from various sources (figures include A Lode Lower & Upper).*

Location	Tonnage (10 <sup>6</sup> )	Pb%	Ag g/t	Zn %	Data Source
Western A Lode	17.6	2.3	29	6	<i>Pasminco Mining unpublished data (1996)</i>
"A Lode" (Measured & Indicated: +3% combined)	39.6	2.9	34	6.4	<i>Pasminco Mining unpublished data (1996)</i>
<i>WtAve WAL &amp; AL</i> "A Lode"		2.7	32	6.2	<i>Pasminco Mining unpublished data (1996)</i>
(mined grade 1979-83)		4.3	31	10.4	<i>Haydon &amp; McConachy (1987)</i>
A Lode (approx)	-	4	30	10	<i>Mackenzie &amp; Davies (1990)</i>

A Lode Lower is the fourth most areally extensive mineralised horizon within the Broken Hill deposit, extending for a known strike length of approximately 1.2 kilometres; mostly within the Pasminco Mine. A possible remnant several hundred metres to the northeast is a component of the Western Mineralisation in the South Mine (Figure 4.2 and 4.3, see also maps STH1480 and NBH6 in Appendix 1). ALL reaches a maximum true thickness of 25 to 35 metres near the 14 Level, is linear in plan and lenticular in cross section (ribbon shaped). However, within the Pasminco Mine, deformation has resulted in ALL forming a convoluted ribbon of sulphide-silicate (mainly quartz) rock that extends from the 7 to the 20 Level between 100m mine grid south to 1200 mine grid south (Figure 4.14). In spite of folding, ALL is the most areally extensive of the seven smaller orebodies at Broken Hill. ALL appears to be thickest where the rhodonite zone is most strongly developed.

ALL is characterised by a quartz, rhodonite-bustamite gangue with minor garnet and hedenbergite. Minor fluorite is recorded by Hudson (1994). Sulphides are dominated by black sphalerite, pyrrhotite, galena, minor loellingite and chalcopyrite. Extensive zones of syntectonic quartz-hedenbergite veining and alteration within garnet quartzite rim the ore zones in deformed regions, particularly in 'Western A Lode' (see section 4.7.6.1 and Chapter 5) where they are well exposed on the 17 Level. Detailed reinterpretation of level plan geology during this study has confirmed that the presence of rhodonite as a distinct horizon or as dismembered segments and clusters within ALL is a reliable defining character of the orebody (see geological maps NBH14 to NBH19 in Appendix 1).

In many parts of the orebody, particularly around the 13 to 15 Levels, the mineralisation preserves an early banding (S0) defined by sulphide and gangue abundances (mainly quartz). Within the main body of ALL there is a distinct, lenticular layer-like zone of rhodonite that is thickest in the centre of the orebody. The rhodonite zone, and adjacent wall rocks, have been penetrated by veins of mobilised sulphides but were probably barren prior to D2 deformation.

The northeastern termination of ALL is a large lenticular body of garnet sandstone which is developed in the area of the 7 to 9 Levels of the Pasminco Mines, in the vicinity of the NBHC Haulage Shaft (e.g. Figure 4.11, see also map sheets STH1370; and NBH10 and 11; contained in rear map folders). The southwestern portion of ALL

diminishes to form a blue quartz horizon within the GQH. It is possible that the Southern A Lode ore zone is a re-development of ALL within this horizon in the South Cross region of the mine (see maps NBH18 to 21, in Appendix 1). However, the stratigraphic context of Southern A Lode is uncertain and requires further work.

Further discussion about the geometry and structural complexity of ALL (and Western A Lode) is presented in Chapter 5.

#### 4.7.6.1. *Western A Lode.*

The ALL position incorporates disjointed sub-zones of ore and mineralisation that have been given various names by previous workers (e.g. Mackenzie and Davies 1990). The most significant of these zones is known as Western A Lode (WAL). WAL consists of three stacked, en-echelon stratiform lenses that are consistent over mineable intervals (Hudson, 1994). The three lenses are named A Lode Lower, Middle and Upper (Hudson, 1994). The individual lenses contain their own distinctive gangue mineral assemblage and grade which reflect those of ALL and ALU respectively. The gangue constituents of AL Middle are not recorded by Hudson (1994).

WAL has been interpreted as a sub-basin of deposition to the north (mine west) of the main development of ore (Hudson, 1994). However, detailed interpretations of the geology of the ALL and WAL positions on successive levels plans from the 14 to the 21 Levels have allowed a correlation of the two zones to be made (see map sheets NBH14 to NBH21 in Appendix 1). What this work has shown is that WAL is continuous with ALL, despite the minor sinistral, west-block up displacement across the BL Dropper Shear adjacent to the hinge of the ZC Antiform (see Chapter 5). The lowest and most significant mineralised horizon in WAL is correlated with ALL based on the presence of the rhodonite zone, which is not present in significant amount (if at all) in any other orebody in the B Lode Horizon or Garnet Quartzite Horizon. The rhodonitic horizon within WAL is stratigraphically continuous with the rhodonitic A Lode Lower. The break between the two bodies of mineralisation is produced by shearing.

Elements of ALL-style, garnet quartzite-associated, rhodonitic mineralisation comprise a component of the re-development of significant mineralisation within the Western Lode Limb to the north of the South Mine. While most of this zone is interpreted to be a part of the B Lode Horizon, the distinctive occurrence of narrow but well developed

lenses and horizons of garnet quartzite and rhodonitic sulphides are more akin to the ALL-style mineralisation of the Pasminco Mine.

#### **4.7.6.2. *Surface Expression of A Lode Lower.***

A Lode Lower and A Lode Upper probably have no surface expression. Like all of the orebodies that overly 2L, their only recognisable surface expression is a large blue quartz-gahnite-garnet rich horizon which forms the southernmost end of the original 'broken' hill and which is now known as South Hill. This outcrop occurs in the area of the former ML 5, now part of the Pasminco Broken Hill Mine. The mineralisation and lode rocks that outcrop at surface represent the B Lode Horizon, a transitional zone between the main orebody position and the regionally extensive Lode Sequence. The narrow lenses and patches of garnet quartzite that outcrop on the southwestern slopes of South Hill (Gustafson, 1939; Noel Carroll pers. comm., 1998) mark the stratigraphic position of the GQH, and therefore the ALL position, at depth.

#### **4.7.7. *A Lode Upper.***

A Lode Upper (ALU) is a relatively small, poorly defined and tectonically modified mineralised horizon hosted within the Garnet Quartzite Horizon (GQH). ALU is distinguishable from ALL by a lack of rhodonite and by its higher stratigraphic position within the GQH. Quartz is the main gangue constituent and it is enriched in pyrrhotite in places. ALU consists of at least one distinct, and up to several small and ill-defined stratiform and structurally mobilised patches of mineralisation that lie between ALL and BL. The resolution of A Lode Upper into a separate mineralised horizon is well defined between cross sections 56 and 68 (800-1000 mine South) but elsewhere in the mine, the broad zone appears randomly mineralised (Hawkins, 1968). The latter state is probably due to deformation and syntectonic mobilisation. In plan view, the zone is best defined on the 14 Level (Figures 4.11, 4.14 and 4.15; see also maps NBH12 to NBH15 in Appendix 1).

Separate ore tonnage and resource grade estimates are very difficult to determine for ALU because production from this zone has historically been included with A Lode Lower (see Figure 4.39).



While the broad distribution of mineralisation within both the ALU and ALL positions is stratabound, considerable syntectonic mobilisation of sulphides has taken place. This has been particularly intense within ALU (see Chapter 5). Hawkins (1968) describes "A Lode" as consisting of high-grade ore lenses and veins that vary from a few centimetres to several metres across, distributed through a "virtually barren gangue". This description is still valid and the patchy, often vein-like nature of ALU (and ALL) means that it was the first zone to be mined by large-scale longhole open stoping at Broken Hill. As such, it has become a significant ore source since the late 1970's and both zones now account for the greater part of ore production at Broken Hill.

ALU is the most structurally complex mineralised horizon in the southwestern region of the BH deposit. It has been strongly affected by brittle deformation, sulphide mobilisation and metasomatism and this has resulted in much movement of sulphide-silicate material into the surrounding garnet quartzite as vein systems and zones of metasomatism. The structural complexity of ALU makes it a difficult orebody to describe without introducing some structural nomenclature. Please refer to Chapter 5 for details of the structures mentioned here.

The mineralisation is quartz-rich and does not contain rhodonite. Quartz-sulphide banding is present but the structural position of the orebody has focussed syn-tectonic quartz vein and sulphide vein formation around the mineralisation and obscured much of the early fabric. Hudson (1994) recognised a distinct upper zone in Western A Lode (see section 4.7.6.1, above), which he recognised as a continuation of ALU to the west of the hinge of the ZC Antiform. In this region, he observed that ALU contains quartz, is enriched in pyrrhotite and formed a distinct "Pyrrhotite Envelope" (a pyrrhotite zone) at the stratigraphic termination of the orebody.

Significant ALU mineralisation does not persist beyond the hinge area of the NBHC Synform and only lower grade and distal ALU mineralisation is present beyond the southern limb of the ZC Antiform (see Chapter 5). Beyond the common limb of the NBHC Synform and the ZC Antiform, distal ALU mineralisation and the mineralised horizon hosting it contribute to the lower grade mineralisation within Western A Lode.

#### 4.7.8. Southern A Lode.

The geology of Southern A Lode has only been investigated in a cursory manner during this study because it lies in large part below the 21 Level of the Pasminco Mine (the lowest level investigated in detail). It was also the focus of intensive mine geological investigation at the time the present project commenced, so only general comments are presented.

In the Southern Cross Shaft area, at the far southwestern end of the Pasminco Mine, a separate, variably mineralised horizon of economic sulphide-silicate mineralisation is developed in an equivalent stratigraphic position that of A Lode at NBHC. It comes into prominence around the 18 Level and lies immediately below BL (see map NBH18 in Appendix 1). It was named Southern A Lode (SAL) by mine geologists in recognition of its occupation of this position (e.g. Mackenzie and Davies 1990). Mining of the zone commenced in the late 1990's and it is now a significant ore source for the Pasminco Mine.

The zone develops around section 93 and by section 98 becomes a significant orebody comprising at least three high-grade sulphide lenses within the keel of the Southern Cross Synform (Mackenzie and Davies 1990). The host fold is a very tight to isoclinal synformal keel that is structurally separated from the main body of the GQH by the D3A Main Shear. The predominant gangue mineral is quartz with occasional garnets in mobilised sulphide veining and fibrous cummingtonite in association with garnet quartzite in areas of retrograde shearing.

Mackenzie and Davies (1990) stated that SAL had average *in situ* grades of 5% Pb and 13% Zn. Their quoted figures differ little from that of BL and adds support to the suggestion that SAL is actually a footwall sub-lens of BL (see section 4.7.9.1). Later grade estimates are significantly lower and in 1996 SAL contained the following mineable resource (Figure 4.40).

The stratigraphic affinities of SAL are uncertain and it is separated along strike from the main body of ALU and ALL by several hundred metres of relatively barren garnet quartzite. The orebody can be seen as a well-defined sulphide horizon in the footwall of BL on geological plans of the 18 Level (see map NBH18 in Appendix 1). On the 19 Level, the zone is a clearly defined horizon that has diverged from BL, and is separated

from it by approximately 200m of intervening garnet quartzite (see map NBH19 in Appendix 1).

The geometry of the lenses is modified by folding associated with the Southern Cross Antiform and the Southern Cross Synform (see maps NBH20 & 21 in Appendix 1). On the 20 Level, the orebody is even more strongly developed, reaching its greatest cross sectional thickness around cross section 106. Where thickened, SAL is completely hosted within the keel of the Southern Cross Synform (the "eastern synform " of Mackenzie and Davies, 1990) though it is uncertain whether the thickening is a stratigraphic feature or is the result of structural thickening. The Southern Cross Synform is discussed in Chapter 5.

**Figure 4.40.** Southern A Lode (+3% combined Pb & Zn). (Pasminco Mining, unpublished data, 1996).

	Tonnes	Pb%	Ag g/t	Zn%
<b>Measured</b>	358,372	3.27	38	4.75
	1,205,629	2.19	25	2.45
<b>Indicated</b>	397,179	3.18	45	5.25
	1,966,198	2.28	32	2.54
<b>Inferred</b>	56,898	2.64	44	5.37
	471,022	1.9	21	2.84

#### 4.7.9. B Lode.

B Lode (BL) is the third largest of the Broken Hill orebodies and was first recognised as the "Siliceous Zinc Lode" by Gustafson et al., (1950). Until recently, it was the next most significant high-grade ore source after 2L and 3L. It is by far the largest of the 'Zinc Lodes', dwarfing the other orebodies that are closely associated with the Garnet Quartzite and B Lode Horizons. It lies at or near the top of the Garnet Quartzite Horizon (Figure. 4.11).

During its main period of production from the late 1940's to the late 1980's, it produced in excess of 46 million tonnes of ore (Burton, 1990). The average mining grade of BL between 1979 and 1984 was 4.3% Pb, 33g/t Ag and 12.4% Zn (Haydon & McConachy, 1987). In 1996, BL had a remaining measured plus indicated primary resource of 4.3 million tonnes at 5.2% Pb, 51g/t Ag and 12.2% Zn. 1.2 million tonnes grading 4.6% Pb, 35g/t Ag and 13.7% Zn remained in secondary pillars (Pasminco Mining, unpublished data 1996). Therefore, the overall tonnage of this orebody was in

excess of 50 million tonnes and it is comparable in size (but not silver and lead grade) to the 45 million tonnes of the Cannington Pb-Ag-Zn deposit to which it bears some geological similarities. Production is still taking place from pillars and lower grade peripheral zones but the majority has been mined out.

BL is the only 'Zinc Lode' to possess stratigraphic continuity throughout the mining operations of the Pasminco Mine. The 20° to 40° southwesterly plunge of this ribbon-like orebody produces a distinct and economically mineralised horizon that extends from just above the Pasminco Mine 4 Level to a position below the 22 Level of the Pasminco Mine Southern Cross Shaft. This gives the orebody a significant economic strike length of some 2.5 km and a mineable depth of over 800m (Figure 4.14). Patchy low grade mineralised zones associated with the BL position (the B Lode Horizon) reach surface on the southwestern slopes of South Hill where they outcrop as banded blue-quartz-garnet-gahnite bands containing minor garnet-quartzite.

BL is a mineralogically simple, sphalerite-dominated orebody with galena as the subordinate sulphide. Despite its apparent mineralogical simplicity, BL is everywhere strongly banded from centimetre to metre scale by a fabric defined by variable proportions of sulphide species (mainly sphalerite) and quartz. Banding within high-grade BL is strongly defined by quartz-rich versus sulphide-rich layers that are less well defined than those in 3L at the Pasminco Mine. Quartz is coarser grained in BL ore than in 3L and there is an appreciable amount of sulphides in the quartz layers. Small, roughly spherical patches of granular garnet sandstone, averaging 1 cm in diameter, are abundant in sulphide-rich layers of BL. Mineralogical layering is also defined by other species such as orthoclase, garnet and apatite. Minor hedenbergite, garnet and occasional fibrous cummingtonite (in retrograde zones) have also been observed (Maiden, 1972; this study). Garnet is particularly prevalent at the peripheries of the main sulphide zone. Hedenbergite and cummingtonite are associated with intensely folded and sheared regions of the orebody. Apatite is a widely distributed accessory mineral in BL (Matthias, 1973). Calcite and rhodonite have been reported in BL by Haydon and McConachy (1987) but these species have not been observed during this project.

Gahnite and garnet are found in altered wall rocks associated with mobilised sulphides and silicified metasediments and lode pegmatite at the orebody margins in the Southern Cross region of the Pasminco Mine. Gahnite, blue quartz and medium to

coarse-grained rounded garnets are also abundant in the upper moderately mineralised 'hangingwall' section of BL, in the transition zone to the regionally extensive B Lode Horizon. These species are only rarely found in the main body of the mineralisation.

#### **4.7.9.1.      *Stratification of B Lode.***

BL is a strongly stratified body consisting of a very high-grade sphalerite-rich zone at the base (the orebody) and a lower-grade upper zone of siliceous, blue quartz mineralisation (usually taken as ore) on the hangingwall side. The high-grade portion of the orebody ranges in thickness from 5 to 50 m (where structurally thickened) but is more commonly around 20 metres thick. BL reaches its widest extent (and largest mineable size) around the 14 and 15 Levels (Figure 4.11 and see maps NBH4 to NBH20 in Appendix 1). Both the lower grade siliceous hangingwall zone and the higher-grade bulk of the orebody are strongly banded.

The upper low-grade zone ranges from 2 to 20 metres in thickness and has a transitional boundary with a thick unit of blue quartz-gahnite-biotite and often sillimanite bearing rock that is known by mine geologists as 'spotted psammopelite' and which is classified in this study as a part of the B Lode Horizon. Spotted psammopelite persists beyond BL as patchy, often lenticular occurrences in association with low grade BL style mineralisation throughout the Pasminco Mine Leases. It is a characteristic lithology of the B Lode Horizon (section 4.4.3.3). There is also an apparently stratiform zone in the hangingwall of BL that is an extension of the low-grade upper zone. This zone forms a part of the so-called 'C Lode' (see below).

A series of small, high-grade sulphide lenses lie within the siliceous hangingwall zone. A series of smaller but related sulphide lenses develop in the footwall of BL, sometimes to become separate orebodies in their own right. The most notable of these is Southern A Lode and possibly a small lens to the immediate northeast of BL that becomes evident on the 14 Level.

The main body of BL and related mineralisation forms an elongate, mound-shaped body with a strongly lenticular shape in horizontal plan view (e.g. Figure 4.11) and cross section. Taken in its entirety, the BL mineralisation forms a complex of high-grade sulphide zones and-sub economic lenses and veins, lower grade peripheral

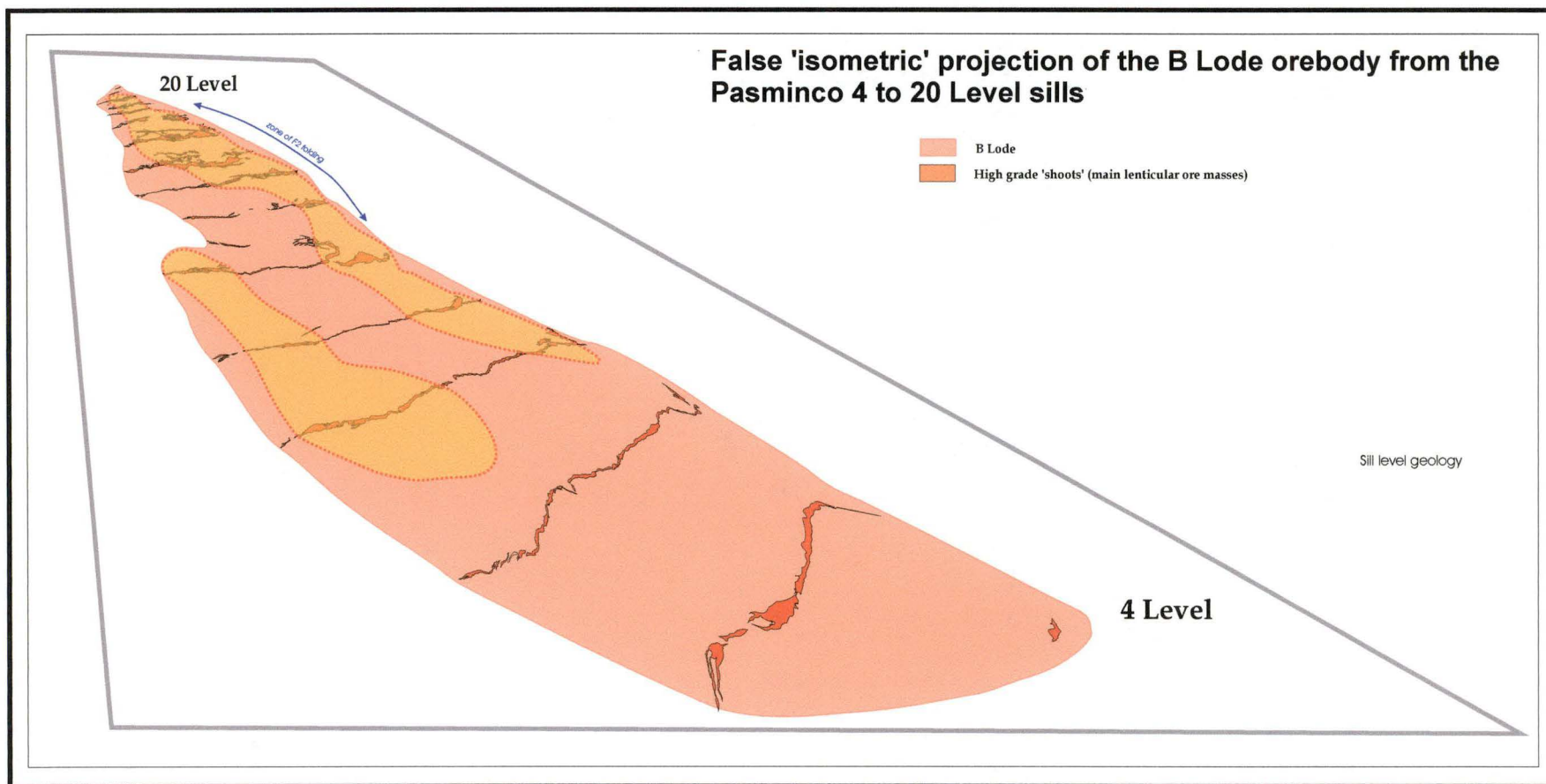
zones and blue quartz bearing metasediments and 'lode' rocks. This close association of mineralised rocks was referred to as the B Lode Complex by Matthias (1973). The hangingwall phases of BL seem to represent a transition from the main mineralising event of the GQH, into the rocks of the overlying B Lode Horizon.

#### 4.7.9.2. *Geometry of B Lode.*

BL can be resolved into two distinct mound-like 'shoots'; one in the northeast and one in the southwest, that are divided by a narrow 'blank' zone (Figure 4.41). The 'shoots' are sometimes linked by a thinner make of high-grade ore but for most of their strike and dip extent they seem to represent lenticular sub-zones of the same high-grade sulphide accumulation. The low-grade blue-quartz-sulphide zone on the upper contact of BL is best developed in association with the northeastern 'shoot'. A similar zone seems to be associated with the southwestern 'shoot' but it is reduced in width, strike extent and down dip continuity compared to the northeastern occurrence. It is possible that the division of the two main shoots is a structural dislocation but no evidence has been found to confirm this during the current study (refer to maps NBH4 to NBH20, in Appendix 1).

Despite the apparent 'shoots' within the orebody, BL is a remarkably elongate orebody that has few of the fold related convolutions that are observed in most other orebodies of the Pasminco Mine. It is therefore a shallowly southwesterly plunging ribbon. This is partly due to the relatively weak development of F2 folds and D3 shearing within the part of the Mine Sequence in which it lies. Only the northeastern section of BL, between the 13 and 15 Levels is significantly affected by deformation. The tight to isoclinal folded geometry of BL in this area is caused by the D<sup>2</sup> ZC Antiform and the D<sup>3A</sup> attenuation associated with the B Lode Dropper Shear/Western Zone of Shearing (Figure 4.15b). The southwestern end of the orebody is affected by intense retrograde D3A shearing (see Chapter 5).

In the Southern Cross area of the Pasminco Mine, BL lies to the north of the effects of folding and attenuation that strongly affect the southern part of the Pasminco Mine (and further to the northeast) and so it retains a large degree of its original shape. In addition, the effects of F2 folding are weakly developed in southwestern part of the Pasminco Mine, possibly because there is a general diminishing of F2 fold intensity towards the southeast (not including the S1L zone). The deformation style and



**Figure 4.41.** False 'isometric' projection of the B Lode orebody looking obliquely down-plunge from the 4 Level to around the 20 level of the Pasminco Mine. Based on geological mapping. The apparent thickness of the orebody is exaggerated at the end of the view nearest the viewer because of the isometric view. Two lens-like 'shoots' are apparent within BL.



intensity has also been influenced by the competent nature of the GQH rocks during D2 folding (Webster, 1993; 1994a).

#### 4.7.9.3. *Stratigraphic context of B Lode.*

B Lode is partly hosted within a package of blue quartz-gahnite-garnet rocks of approximately psammopelitic composition and which are known on the Pasminco mine as 'spotted psammopelite'. BL lies at or near the upper contact or hanging wall of the GQH. Matthias (1973; 1974) defined the layered sequence of rock types hosting BL as the "B Lode Complex". He recognised it to consist of a sequence of variably mineralised siliceous metamorphic rocks that, below BL, consisted of a series of sub-parallel to parallel lode pegmatite intrusives interlayered with sulphide layers, variably mineralised garnet quartzite and thin layers of chlorite-sericite schist. In the vicinity of cross section 57, Mathias (1973) recognised a sequence overlying BL that consisted of gradational lithologies including lode pegmatite, weakly to strongly mineralised garnet quartzite, blue quartz rocks, thin "metabasites", rare and localised calc-silicates and garnet-sillimanite-staurolite (sulphide) gneisses, quartzite's and schists.

Southern A Lode (and possibly Southern 1 Lens) and a number of minor, unnamed bodies of mineralisation occur in the footwall and hangingwall of BL. They are similar in mineralogy and their close association with BL suggests that they are 'satellites' of the main BL mineralisation.

The southwestern end of B Lode passes beyond the Garnet Quartzite Horizon, persisting for a further 200 to 300 metres, before diminishing into a well-mineralised position and then merging into the spotted psammopelite-blue quartz bearing basal unit of the Lode Sequence (the B Lode Horizon) on the Pasminco Southern Leases (Figure 4.8). The upper contact of the BL mineralisation merges into the overlying spotted psammopelite/blue quartz-garnet-gahnite rocks of the B Lode Horizon.

The southwestern and northeastern ends of BL and the overlying low-grade mineralisation and mineralised spotted psammopelite persist beyond the Garnet Quartzite Horizon for 200-300 metres southwest and for a similar distance to the northeast of its termination. The northeastern continuation of BL forms part of the mineralisation known as "C Lode" by mine geologists (see section 4.7.10). Apart from

spotted psammopelite, the host rock of much of the distal BL mineralisation in the Southern Cross area at the southwestern end of the Pasminco Mine is a fine-grained, garnetiferous psammite that tends to garnet quartzite in texture. Such fine-grained garnetiferous psammites are commonly associated with mineralisation throughout the mine leases in areas such as the Potosi orebody (4.5 Horizon), Barrier Consolidated prospect, the Silver Peak prospect and in the North mine. They have also been observed in the mineralised horizons in the north wall of the Kintore open cut in CML 6, which has been correlated with the various "Zinc Lodes" of the Pasminco Mine.

Fine-grained-garnet psammite is very reminiscent of garnet quartzite in texture and it could be interpreted as a less manganese-enriched equivalent of garnet quartzite and the GQH. Such fine-grained garnetiferous psammites probably represent the stratigraphic position of A Lode Lower within the Lode Horizon.

On the 17 Sill at Southern Cross, the southwestern part of BL merges with intensely silicified, saccharoidal psammites with abundant blue quartz and fine-grained garnet. The silicification, and certainly the saccharoidal texture, appears to be related to metasomatism of a style which is similar to that associated with D3A attenuation in 2L and 1LL where they are juxtaposed with sheared clastic metasediments such as on the eastern side of the 20 Level sill in the Pasminco Mine (Webster 1994a). The alteration of pegmatite and metasediments is also similar to that seen adjacent to 3L in the North Mine (see section 4.7.3.2 above). The saccharoidal texture diminishes away from the contact with mineralisation over a transition zone. Mobilised sulphides and associated silicification have extensively mineralised the immediate contacts of lode pegmatites within the 'southern' BL area and this has been mined as ore in places (Figure 4.10d).

Low grade mineralisation, similar in style to the distal portions of BL, is found hosted within spotted psammopelite throughout the Pasminco leases to the northeast and southwest of Broken Hill; at White Leads and Rising Sun (southwest), and in the Silver Peak (section 4.7.11) and Barrier Consolidated prospects (northeast). Low-grade intersections of such mineralisation are common in the B Lode Horizon position throughout the Pasminco leases.

The B Lode Horizon, consisting of variably mineralised spotted psammopelite and fine-grained garnet psammite, persists as the only regionally represented component

of the BH mineralisation on a district, and possibly regional scale (see section 4.4.3.3 above).

#### **4.7.9.4.      *Lode Pegmatites associated with B Lode.***

BL was extensively intruded by pegmatite dykes, particularly on the southern (footwall) side, very early in its geological history. They form elongate lenses and sheets that are parallel or sub-parallel to the contacts and banding of orebody and its associated rock types. The dykes have been folded by F2 folds while preserving the transgressive relationships to the ore horizons. The dykes are also strongly silicified, sericitised and mineralised in places, usually where they are in direct contact with the sulphide orebody. The bands of orthoclase identified within BL by Mathias (1973) are probably deformed dykes that have been mineralised by syntectonic mobilisation of sulphides, as is observed in the B Lode mining areas of the Pasminco Mine on the 17 and 18 Levels.

Large tabular bodies of intrusive lode pegmatite intersect the B Lode Horizon and GQH, and in plan, crosscut the strike of these units. Intrusions of pegmatite occupy a stratigraphic position on the hanging wall of the GQH and extensively intrude the hanging wall of BL. Dykes are also common in the footwall of BL, and above A Lode where they are known as the 'Separation Pegmatites'. The Separation Pegmatites are mildly transgressive of the stratigraphy of the GQH and the BL complex, and these relationships have been deformed by F2 folding. This observation shows that the pegmatite intruded the B Lode Horizon and the GQH sequence prior to D2.

#### **4.7.9.5.      *The Surface Expression of B Lode.***

Economically significant B Lode mineralisation does not outcrop. The orebody rapidly fades out up plunge to the northeast above the Pasminco Mine 6 Level sill. There is a weak development on the Pasminco 4 Level (see map STH625 in Appendix 1; also shown on Figure 4.41) and a lenticular, isolated occurrence (probably a shear-hosted pod) was recorded on the South Mine 425 Level by Gustafson (1939) (see map BHP5C in Appendix 1) where it was referred to as 1 Lens. However, there are surface exposures of the near-ore lithologies of the B Lode Horizon intersecting the surface on the southwestern slopes of South Hill in the northeastern part of the Pasminco Mine (Figure 4.1 and 5.1, both in separate map folder). The outcrop consists of a blue

quartz-garnet-gahnite rich horizon that is strongly banded, with variations in garnet, gahnite and blue quartz proportions and which contains gossanous patches and specks of goethite after sulphides. Most such bands of gossanous material are parallel to the well-developed banding (Figure 4.10a (on right) and Figure 4.1).

The sulphide-rich zones of the Western Mineralisation are similar to the lower grade mineralisation at the peripheries of B Lode and A Lode in the Pasminco Mine. They have similar mineralogy, host rock associations and stratigraphic position in the Lode Horizon. These features suggest that they are closely related (Webster 1996a; section 4.4.3.3; map NBH6 and STH1480 in Appendix 1). If this is true, then 3L and 2L are the only orebodies that outcropped at Broken Hill because the Western Mineralisation lies at depth in the central mining field. None of the other orebodies in the Pasminco Mine intersected the present topographic surface.

#### 4.7.9.6. *B Lode-style Mineralisation of the 'Western Lode Limb'*

The B Lode Horizon is poorly defined to the immediate northeast of the BL mineralisation in the upper levels of the Pasminco Mine. Despite the weak but well-defined outcrop on South Hill, there are few known occurrences of B Lode Horizon in the boundary region between the South Mine and the Pasminco Mine and there are few drill holes intersecting the horizon at depth in this region of the field.

Approximately 300 metres to the northeast of the surface expression of the B Lode Horizon on South Hill, two elongate, 'satellite' bodies (shoots) of mineralisation known as the Western Mineralisation (WestMin) and Centenary Mineralisation (CMin) (Gentle, 1968; Haydon and McConachy, 1987) develop at depth, in a down-dip position from the main orebodies (Figures 4.14, 4.2 and 4.3). The WestMin and CentMin occurrences coincide with a very strong redevelopment of a B Lode Horizon-style package of rocks and consist of bands and stringers of sulphide hosted within garnet quartzite. The WestMin is the largest re-occurrence of significant mineralisation within the B Lode Horizon outside the Pasminco Mine. Accessory minerals include rhodonite and hedenbergite with minor cummingtonite and grunerite in adjacent garnet quartzite (Haydon & McConachy, 1987).

The WestMin and CentMin are hosted within a planar "sheet-like layer" composed of garnet-biotite quartzite containing variable amounts of apatite, or a quartz-gahnite

rock containing variable amounts of sulphides. Siliceous biotite garnet gneiss is interbanded with the more distinctive rock types and is weakly mineralised (Gentle, 1968). The western lode limb package and its associated lode rocks occupy the majority of the position of the Lode Sequence to the north of CML 7 and within ML 1249. The Western Lode Limb extends from the Pasminco Mine to the British Fault (Gentle, 1968) (refer to map STH1480 in Appendix 1).

The Western Lode Limb is interpreted to represent the B Lode Horizon, but is a separate remnant of significant mineralisation that is stratigraphically separated from the distal northeastern B Lode Horizon position by an apparently unmineralised but poorly drill tested part of the LodSeq. The dislocation of the WestMin and B Lode Horizon-ALL in the Pasminco Mine is not yet explained but is probably due to stratigraphic discontinuity, or structural dislocation. Future exploration work should resolve this problem.

The WestMin consists of 15 million tonnes of mineralisation grading 2% lead, 30g/t silver and 3% zinc (Pasminco unpublished data; Haydon and McConachy 1987). It has many mineralogical and textural similarities to weakly mineralised packages of rocks that are observed in both the southwestern and northeastern extremities of BL in the Pasminco Mine. The composition of the zone includes primary quartz, garnet, biotite, gahnite, apatite, clinozoisite and minor hedenbergite (Gentle, 1968). A sporadic rhodonitic gangue has been observed in places, as has a patchy but often well-developed garnet quartzite zone (Haydon and McConachy, 1987). The garnet quartzite development is a correlate of the Garnet Quartzite Horizon in the Pasminco Mine and represents an A Lode-style position within the zone.

The CentMin represents a distinct zone of mineralisation (approximately 9 million tonnes grading 2% lead, 30 g/t silver and 3% zinc (Haydon and McConachy, 1987)), which is structurally dislocated from the Western Mineralisation by the Globe Vauxhall Shear Zone. It is mineralogically distinct from the WestMin, consisting of blue quartz, gahnite, quartz, garnet, calc-silicate, +/- epidote, clinozoisite, hedenbergite, calcite and some rhodonite. It is therefore similar to ALL (or possibly 1L). Some garnet quartzite is also associated with the CentMin (Haydon and McConachy, 1987).

The Western Mineralisation on the 1000 and 1480 Levels of the South Mine has been developed underground and geological mapping is available. Interpretation of this data suggests that the geometry of the zone is controlled in part by a series of southwest plunging 'S' vergence folds. They have the same vergence as the folds in the main orebodies. Significant sulphides are contained within of two distinct shoots that appear to be hosted within F2 fold keels (Figures 4.2 and 4.3 or maps NBH6 and STH1480 (for detail) in Appendix 1).

The WestMin and CentMin are bounded by well-developed occurrences of Potosi gneiss representing both the 'underwall zone' (two distinct units associated with thin amphibolites) on the footwall and the Upper Potosi Type Quartzofeldspathic Gneiss on the hangingwall (two distinct units in places).

#### **4.7.10. 'C Lode'.**

A well-defined and apparently stratiform zone of low-grade mineralisation is developed on the northern (hangingwall) side of BL, mainly between the 6 and 10 Levels of the Pasminco Mine (Maps STH1070 to STH1480, in Appendix 1). It has been named "C Lode" by Pasminco geologists (Mackenzie and Davies, 1990). The relatively limited 120m-strike extent of the best-developed zone of mineralisation within this horizon has been defined between mine sections 37 and 43 (Mackenzie and Davies, 1990). The reinterpretation of the geology of the main production levels of the Pasminco Mine has resolved many of the details of the structural and stratigraphic relationship between this zone, BL (and the "B Lode Complex"), distal BL mineralisation and the B Lode Horizon.

"C Lode" consists of variably developed sphalerite-galena-pyrrhotite mineralisation within a weakly mineralised 50-150m thick package of spotted psammopelite and blue quartz-rich gahnite-garnet lode (Carruthers 1965; Haydon and McConachy 1987). Mine definition drilling has shown that there is a low-grade stratiform component to "C Lode" (A Wilson, Pasminco Mining unpublished data) and the current study has supported this finding; defining the zone between the 6 and 9 Levels of the Pasminco Mine (Figure 4. Maps STH1070 to STH1480, in Appendix 1). However, the economically extractable parts of "C Lode" actually comprise not only the stratiform zone but also shear-hosted, structurally mobilised mineralisation associated with the

axial plane of the ZC Antiform and which were named "Axial Plane Orebodies" (APO's) by J. Stockfeld (Pasminco Mining unpublished data, 1996)

It can now be shown that "C Lode" is not a truly separate mineralised horizon lying above BL, but is actually the distal northeastern extension of BL that has been folded back upon itself by virtue of its position on the common limb of the NBHC Synform and the ZC Antiform. The effects of folding on this horizon have been accentuated by sinistral shearing in the area, which has partially transposed and displaced the weak mineralised zone to the southwest. "C Lode" only now appears to be a separate mineralised position because it is attenuated and structurally offset from BL by the effects of D2 folding and D3 shearing. The main plane of shearing is the B Lode Dropper Shear (the "Axial Plane Orebody", or dropper of Stockfeld, 1993a, 1993c and 1993d; see Chapter 5). This structure and its related planes of movement produced the offset between BL and "C Lode", in a similar manner to the offset and dislocation between A Lode Lower and Western A Lode.

"C Lode" represents the former northeastern continuation of the B Lode orebody and low-grade stratiform mineralisation within the B Lode Horizon, a rock package that is very similar to that seen at the southwestern end of BL. The stratiform, mineralised blue-quartz and spotted psammopelite-hosted "C Lode" mineralisation bears a striking similarity to the distal margins of 'southern' B Lode, between the 15 and 17 Levels of the Southern Cross area; at the southwestern end of the economically significant mineralisation. In this region, BL diminishes in size and grade, as the Lode Sequence diminishes, to eventually merge into the Lode Horizon of the Pasminco southern leases. The regional scale mineralisation previously defined as 'C Lode' by mine geologists and thought to lie within a "C Lode Horizon" (Webster 1996a, Morland and Webster, 1998) is now recognised to represent the distal BL position within the B Lode Horizon (see section 4.4.3.3).

B Lode, the third largest BH orebody, is now recognised to lie at the stratigraphic top of the mineralised system. 3L, the second largest orebody lies at the base of the system. The two orebodies have many geological characteristics in common, which are discussed further below (section 4.8). Peripheral BL-style mineralisation is now recognised to represent the stratigraphic link between the main orebodies, the B Lode Horizon of the Lode Sequence and to persist throughout the district in the regionally significant Lode Horizon (see the next section).



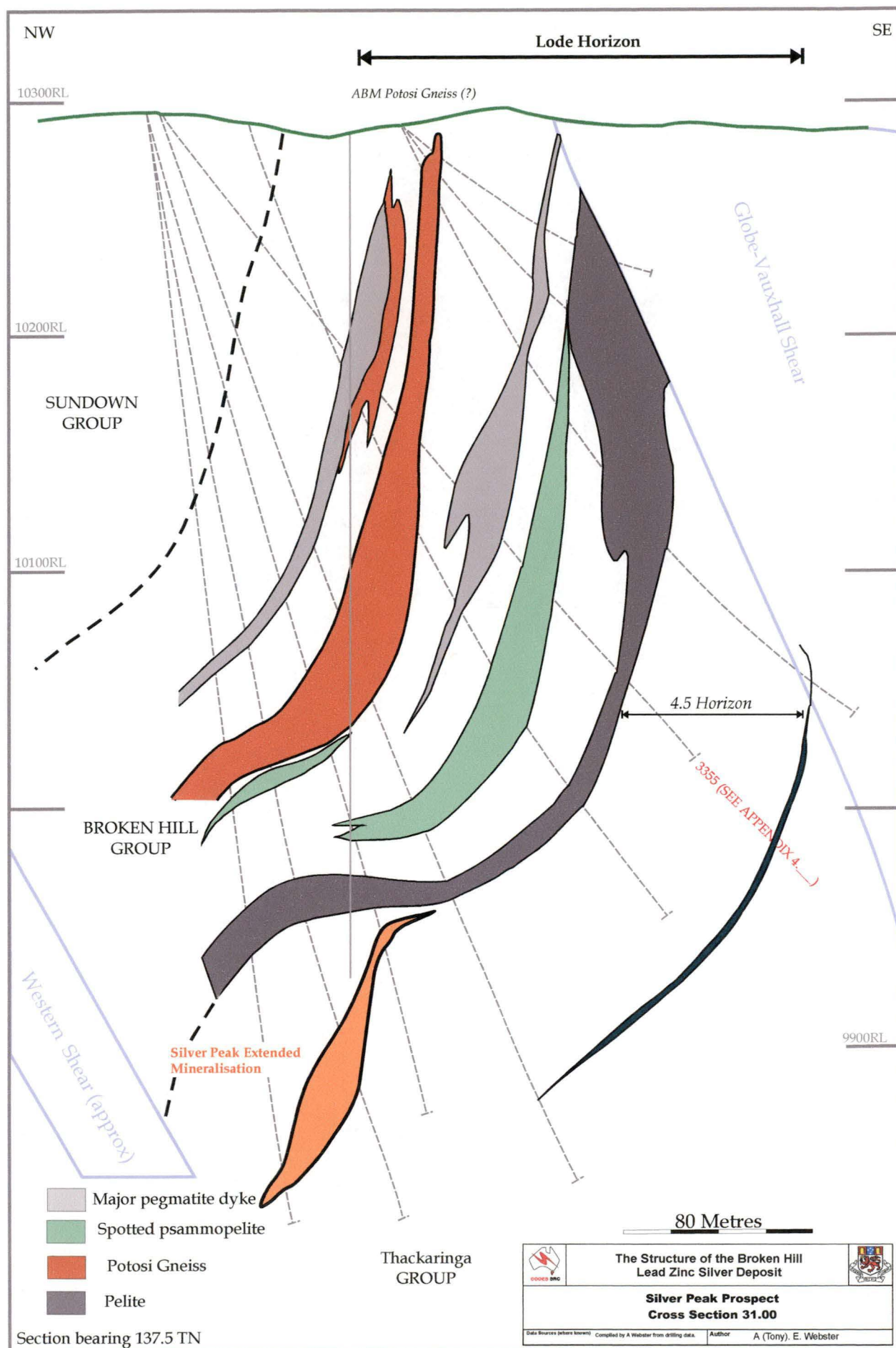
Significant occurrences of distal B Lode style mineralisation occur in the Lode Horizon, one of which is known as the Silver Peak Extended Mineralisation (see section 4.7.11, below).

#### **4.7.11. The Silver Peak Extended Mineralisation.**

The Silver Peak Extended mineralisation represents one of several small lead-silver-zinc deposits contained within the Lode Horizon that bear a strong similarity to distal B Lode positions in the Pasminco Mine and to the Western and Centenary Mineralisation in CML7 (discussed in section 4.7.9.6, above). It occupies the same stratigraphic position in the Lode Horizon as the main orebodies, lying within the Hores Gneiss of the Broken Hill Group as defined by Willis et al., (1983) and Stevens et al., (1983). The Silver Peak mineralisation is hosted within the largest currently defined occurrence of B Lode Horizon-like rocks outside the main mines area (King and Thomson, 1953; A. Webster, unpublished data 1994). It consists of approximately 2 million tonnes of mineralisation grading 3.3% Pb, 32g/t Ag and 1.8% Zn (Figure 4.42).

The prospect is located approximately 5 kilometres northeast of the City of Broken Hill and 2.5 kilometres north of the North Mine. The Silver Peak Extended mineralisation lies just over 7 km northeast of the surface expression of the BL orebody at the southwestern end of the field. The Silver Peak mineralisation occurs immediately to the northeast of the recently mined Potosi zinc-lead-silver deposit (Larsen, 1994) and lies adjacent to the deeper extensions of that orebody that occur in the adjacent 4.5 Horizon.

The deposit was originally mined in the latter part of the nineteenth and early twentieth centuries but only a few hundred tonnes were removed. It was also intensively explored in the late 1960's and early 1970's by North Broken Hill Ltd who developed an exploratory shaft to bulk test a drill-defined block of zinc-rich mineralisation. Apart from mining in the latter part of the 19th Century (economics unknown) and the bulk test of the 1970's, the mineralisation has never been economically mined.



**Figure 4.42.** Cross section of the 'old' Silver Peak area, Pasminco northern leases. Showing the reduced thickness of the Lode Horizon in a mineralised position distal to the main orebodies. The stratigraphy of the Lode Horizon remains remarkably constant beyond the main orebody position and most elements of the Mine Sequence, apart from the main orebodies, can be recognised. For detailed descriptions of the lithologies of the Lode Horizon, see the drill hole log for DDH 3355, which is presented in Appendix 5.3.

#### **4.7.11.1. *Stratigraphy of the Silver Peak Area.***

The outcropping geology of the Silver Peak area is dominated by 40 to 50 metre-wide strip of the Lode Horizon (Hores Gneiss) sandwiched between the Sundown Group metasediments and the Western Shear to the north and the Globe-Vauxhall Shear Zone (GVSZ) to the south. Unit 4.5 only outcrops in the southeastern part of the prospect because shearing associated with the south dipping Globe-Vauxhall Shear truncates it at depth. A narrow amphibolite (probably part of the Town Amphibolites), known by Pasminco as Unit 4.4, never reaches surface in the Silver Peak area due to the GVSZ, but is consistently present at depth. Strata dip steeply east near surface but roll over to dip steeply west to near vertical with depth. The strata then flatten off to the west before finally being truncated by the Western Shear.

The mineralised part of the Lode Horizon at Silver peak outcrops as a long low ridge, with the more resistant lode rocks, spotted psammopelite, Upper Potosi Gneiss and associated stratiform pegmatite's outcropping on the crest and western slope of the ridge.

Large stratiform bodies of pegmatite occur at the Broken Hill Group-Sundown Group contact and especially in association with the pelite unit that usually marks the base (Pasminco Mine unit 4.6 Pelite). A large lenticular, stratiform body of pegmatite also occurs on the lower contact of a UPG unit within the centre of LodSeq and persists throughout much of the strike length of the prospect. The three stratiform pegmatite sills form important local stratigraphic markers within the Lode Horizon in the Silver Peak area.

#### **4.7.11.2. *Mineralisation at Silver Peak.***

Mineralisation is contained within three main lenses, named Upper, Middle and Lower Lens, in reference to their stratigraphic position within the Lode Horizon (Pasminco Mine "Unit 4.7"). A fourth body of mineralisation occurs in the same stratigraphic position as Lower Lens, between northern leases cross sections 29.25 and 28.5. This mineralisation does not seem to be connected to the main Lower Lens and is named Lower Lens North.

Each of the three mineralised stratigraphic positions is hosted within coarse-grained garnet 'spotted psammopelite', which is variably pelitic in composition. Spotted psammopelite is closely associated with variably Potosi gneiss-like quartzofeldspathic gneiss and Potosi type gneiss. Where mineralisation diminishes, the Lode Horizon is dominated by Potosi type gneiss and Potosi-like quartzofeldspathic gneiss.

Bodies of mineralisation occur as ribbons within the Lode Horizon. They are contained within spotted psammopelite lenses and are lenticular in form. The Upper, Middle and Lower Lenses all reach their greatest thickness in the same region of the prospect and can be described as stratigraphically stacked. Individual lenses are composed of narrow vein-like bodies of sulphides and quartz of various widths, with barren material in between. Sulphide lenses are clustered together within the spotted psammopelite 'envelopes' (this relationship is seen in outcrop immediately to the southwest of the Old Silver Peak Shaft).

Mineralisation is generally siliceous, containing blue quartz and gahnite, with retrograde sericitic muscovite replacing sillimanite and pegmatitic segregations. Mineralised bands are most often composed of strongly blue quartz and gahnite-altered pegmatitic segregation's (blue quartz lode) though not all blue quartz hosted mineralisation was originally pegmatite. Clear quartz, with lesser biotite, and retrograde sericitic muscovite, are the next most common gangue constituents. Sulphides typically include galena, sphalerite, pyrrhotite, chalcopyrite (mostly minor) and occasional traces of arsenopyrite. Gold is a very minor to trace constituent. Traces of pyrite occur along late-stage fractures in the mineralised areas.

#### **4.7.11.3. *Structure of the Silver Peak Mineralisation.***

Mineralisation has been extensively redistributed by syn-tectonic mobilisation and recrystallisation during D2, and smaller pegmatitic segregation's are often strongly differentiated by the intense S2 cleavage fabric formed during D2. Mobilised sulphides have 'mineralised' earlier pegmatitic segregations, veins and dykes and often show vein-like forms, or follow S2 foliation trends. The pervasive S2 foliation is most intensely developed in pelitic rocks, while psammitic and quartzofeldspathic rocks preserve S1 very well (see section 5.3.1). S2 causes extensive differentiation of the dominant D1 fibrolite bundles. Later retrogression has reduced generated sericite. Gahnite is usually replaced by sericite, most commonly as marginal rims.

#### **4.7.11.4.      *Silver Peak Mineralisation and Pegmatite***

Intrusive pegmatite sills are ubiquitous in the metasediments associated with the Silver Peak Extended mineralisation. Most dykes are located at the contacts of pelitic and psammitic or psammopelitic units layers and so they tend to closely follow the predominant layering within the gneissic package. Most pegmatite's in the Silver Peak area have been strongly sericite altered and silicified (often associated with strong hydrothermal brecciation). Blue quartz alteration and gahnitisation of pegmatite's is also common. Coarse red garnets occur in syntectonic zones of silicification.

There is a spatial association between mineralisation and stratiform pegmatite bodies. This relationship is particularly evident within the Lower Lens where the greatest development of high-grade mineralisation occurs at the contact of the lower pegmatite. Some pegmatite sills have been mineralised around the margins by mobilised sulphides. Sulphide-bearing pegmatite was presumably formed when sulphides were locally mobilised, syn-D2, in association with the silicification, sericitisation and 'gahnitisation' processes that also affected some pegmatite during deformation and metamorphism.

### **4.8. OREBODY CLASSIFICATION.**

#### **4.8.1.      Introduction.**

The relative lead to zinc content of each of the Broken Hill orebodies is variable but there is a broad zonation recognised in the multiple lenses of the Pasminco Mine. This variation has traditionally led to the classification of two categories of ore lenses; the Zinc Lodes, where zinc content is greater than lead and the Lead Lodes where lead is greater than zinc (e.g. Gustafson, 1939; Burrell, 1942; Gustafson et al., 1950; King and O'Driscoll, 1953; Mackenzie and Davies, 1990; Haydon and McConachy, 1987; Wright et al., 1993). However, in practice, this definition is overly simplistic because all the ore lenses have comparable zinc grades but vary widely in their lead content. The lead grade variation is not random, and there is a relative decrease in lead content in the ore up-sequence from 3L to B Lode. 3L also shows a decrease in lead from northeast to southwest (Plimer, 1984). The only orebody that shows a consistently higher percentage of lead to zinc is 2L, which is therefore the only orebody that can truly be

classified as a "Lead Lode", based on metal ratios, for its entire strike length. Therefore, orebody types cannot be defined by lead to zinc ratios alone.

The 1 Lens orebodies were classified as "Zinc Lodes" (e.g. Mackenzie and Davies, 1990) but have few geological features in common with the overlying orebodies with which they are categorised, except a higher zinc than lead content. As was shown above (section 4.7.5.2) the 1L orebodies are geologically most similar to 2L and are branches of that orebody.

There is a transitional sequence from 3 Lens to B Lode in which lead diminishes as a component of the orebodies (Webster, 1994a).

The transition from lead-rich to less lead-rich orebodies in the sequence from 3 Lens to B Lode occurs over the same interval in which other changes occur in the wall rock associations of the orebodies. The changes include a loss of clastic metasediments; amphibolite and calc-silicate horizons in near-ore positions and the development of the Garnet Quartzite and B Lode Horizons. Gross changes also occur in the gangue mineral assemblages of the orebodies. Calcite is an important component of 2L, 1LL and 1LU but is mostly absent in the overlying lenses, suggesting that the calcium component of the ore depositional system diminished, concomitant with an increase in primary quartz deposition. Quartz is only a significant component of 2L, 1LL and 1LU in the Pasminco Mine, where the orebodies reach their greatest stratigraphic diversity. Manganese is an important component of 2L in the southwest of the field (also in the region of greatest stratigraphic diversity) but diminishes upwards to ALU. Very little calcium or manganese seems to have been deposited with ALU and BL sulphides.

The present study has increased the understanding of the stratigraphy of the orebodies, clarified their relationships with the Lode Sequence strata and further defined their internal stratification. This information shows that the BH orebodies fall naturally into two distinct categories (modified after Morland & Webster, 1998), the;

- **Siliceous orebodies**; which are associated with the manganiferous rocks of the Garnet Quartzite and B Lode Horizons, and the

- **Calcitic orebodies;** which are mostly hosted by clastic metasediments containing calcium-rich lithologies in the Underwall Zone of the Footwall Sequence (Webster, 1994a).

The Siliceous and Calcitic orebodies show several weakly transitional characteristics (e.g. rhodonite occurs in 2L and ALL) but there is a sharply defined boundary between the two classes. The boundary lies between 1LU and ALL and is marked by the loss of calcite and the concomitant incoming of quartz as the major gangue component of high-grade sulphide mineralisation.

The following sections outline the proposed new classification.

#### 4.8.2. Calcitic Orebodies.

Three orebodies are classified as 'Calcitic orebodies':

- 2 Lens,
- 1 Lens Lower, and
- 1 Lens Upper.

The three orebodies share a suite of common characteristics, which are variably developed in each. These features include;

- They are hosted mainly within clastic metasediments,
- They are be associated with a suite of calcic lithologies (amphibolite, potosi type gneiss, calc-silicate horizons) in the adjacent metasediments,
- They have little or no significant association with 'lode rocks',
- They have distinct sulphide rich (+/-quartz) upper zones in sharp contact with banded calcitic ore,
- They possess a calcite gangue, and
- They possess rhodonite layers (particularly in the southwestern end of 2L below the 12 Level (e.g. Gustafson et al., 1950).

The calcitic orebodies are contained within a single sequence of clastic psammite, psammopelite and pelite (the Underwall Zone), in association with calcic lithologies,



including metasediments. 2L lies immediately below the Garnet Quartzite Horizon (GQH), hosted within a relatively monotonous package of psammopelites, psammities and pelites. 1LL and 1LU partly lie within the same rocks but merge with the GQH down-plunge to the southwest.

2 Lens has virtually no association with garnet quartzite, blue quartz lode rocks or garnet sandstone; all of the rock types that are so commonly associated with the Siliceous orebodies. A thickening wedge of clastic metasediments develops between 2L and the base of the GQH, down-plunge to the southwest, through the Pasminco Mine. 2L encounters the lower contact of the GQH for the first time just prior to its termination.

2L contains conspicuous occurrences of fluorite (Gustafson et al., 1950), which forms a significant component of distinct layers in the ore (Webster, 1994a). Gustafson et al., (1950) also note that green or white, seldom red or brown fluorite occurs in several places within 2L. Fluorite has also been noted in 1L (probably 1LL) by Gustafson et al., (1950).

1 Lens Lower and 1 Lens Upper contain very high values of both lead and zinc, for which they have traditionally been defined as "Zinc Lodes". However, the geology of these orebodies more closely resembles 2 Lens, of which they are 'branches' (see section 4.7.5.2, above). Like 2L, they are hosted by clastic metasediments (for a considerable part of their strike length), they possess a dominantly calcitic gangue, contain some fluorite (Gustafson et al., 1950), and possess siliceous high grade sulphide zones on their upper margins. They are very rich in lead and have only a relatively poorly developed association with the garnet quartzite. The 1L orebodies only gain stratigraphic contact with a GQH in the southwestern part of the strike length, merging with it below the Pasminco Mine 17 Level. They always lie at the base of the GQH at the interface between garnet quartzite and clastic metasediments. Where they are contained within the GQH they always lie at its base, at the interface between garnet quartzite and clastic metasediments. The 1L orebodies lie at the transition between clastic sedimentation within the Lode Horizon and the large-scale formation of 'lode rocks' in the GQH and B Lode Horizons that accompanied the deposition of the Siliceous orebodies.

There is a strong stratigraphic association between garnet sandstone, 1LL and 3L (e.g. King and O'Driscoll, 1953). The northern margin of 1LL pinches out into garnet sandstone at its along-strike termination just above the 20 level of the Pasminco Mine (Figure 4.13).

Calcite and fluorite are rare within the rocks of the Willyama Supergroup. The close spatial association of these minerals within 2L and 1L, and in the underlying 3L, the former of which are similar in so many other ways, strongly suggests a genetic link between 2 Lens, 1L and probably 3 Lens.

#### 4.8.3. 3 Lens.

3L possesses a number of features that, in combination, set it apart from all other orebodies at Broken Hill. Such features include:

- A fluorite gangue layer (Figures 4.22, 4.23, 4.24 & 4.28),
- A change in the relative abundance of zinc relative to lead from northeast to southwest through the deposit (e.g. Plimer, 1984, Figure 4.19),
- A primary quartz gangue,
- an association with separate garnet quartzite zones at both the northeast and southwest ends of its strike extent, and
- A very strong association with well developed garnet sandstone horizons (altered garnet quartzite).

Most of these features suggest that 3L is more closely related to the Siliceous Orebodies, than it is to the Calcitic Orebodies. However, 3L also possesses many features that are only seen in the Calcitic Orebodies, including; 2L-like calcitic zones, which are developed in the far southwestern end of the orebody and which possess similar metal ratios to 2L (Gustafson et al., 1950); very high lead grades relative to zinc and a clastic metasedimentary wall rock association.

3L has traditionally been classified with 2L as a "Lead Lode" (e.g. Gustafson, 1939; Gustafson et al., 1950; Haydon and McConachy, 1987). However, in the Pasminco Mine, 3L contains more zinc than lead, and so cannot strictly be defined as a "Lead Lode". 3L also has several other geological characteristics that suggest it is more like

the other traditional "Zinc Lodes" (Siliceous orebodies) than a "Lead Lode". These features include:

- A mainly quartz gangue,
- An association with small zones of garnet quartzite on its southwestern and northeastern margins, and
- A strong association with blue quartz-bearing 'lode rocks' (that are probably represent syntectonic alteration, at least in major part)

3L is significantly different in gangue complement to the bulk of 2L and 1L. It possesses a mainly quartz gangue that is similar to only relatively thin, siliceous and massive sulphide layers within 2L and 1L (e.g. Figure 4.36), and has variable metal ratios. However, unlike most of the Siliceous orebodies (ALL being the exception), 3L contains abundant fluorite and includes large masses of rhodonite in the northeastern part of the field (where it is a major constituent of this orebody). It has these features in common with the Calcitic orebodies and there are others. 3L is hosted within clastic metasediments, only developing relatively minor marginal garnet quartzite zones in some areas. Calcitic mineralisation forms a component of 3L in the Pasminco Mine, where a distinct 2L-like zone develops in the orebody horizon (see section 4.7.3.3 above). Calcitic ore within 3L was found to have similar metal ratios to 2L or by Gustafson et al., (1950). Like 1LL, 3L has a widespread association with peripheral garnet sandstone zones; actually terminating naturally along strike into large masses in the centre of Pasminco Mine, in the upper levels of the Junction Mine and in the lower levels of the BHP Mine.

3L is interpreted to be a 'hybrid' style of mineralisation, possessing characteristics of both the Siliceous orebodies (see below) and the Calcitic orebodies; but is more like the Siliceous orebody end of the spectrum.

#### **4.8.4. Siliceous Orebodies.**

The Siliceous orebodies were defined as the "Quartzitic Orebodies" by Morland & Webster (1998). They comprise all of the orebodies that overly 1 Lens Upper and are characterised by a relatively simple gangue mineralogy dominated by quartz and garnet. The Siliceous orebodies are spatially associated with the largest development of mangiferous 'lode rocks' in the Lode Sequence, being mainly hosted within the

Garnet Quartzite Horizon (GQH), and to a much lesser degree, the B Lode Horizon. The orebodies lie at particular levels within the GQH and include:

- B Lode,
- Southern A Lode,
- Southern 1 Lens,
- A Lode Upper, and
- A Lode Lower

The Siliceous orebodies are mostly restricted to the southwestern part of the mining field, within the Pasminco Mine and all possess a greater percentage of zinc than lead.

The lowermost Siliceous orebody is ALL, which is the only one of this group that possesses a significant occurrence of rhodonite. In common with 3L and 1LL, ALL also terminates with a stratiform garnet sandstone unit (north-eastern end). The rhodonite zone in ALL suggests some degree of continuity of depositional process from the Clastic to Siliceous orebody positions

B Lode is the largest and most complex orebody of this group and lies at the top of the sequence. It is closely associated with the blue quartz bearing rocks of the B Lode Horizon, merging into the spotted psammopelite/blue quartz-garnet-gahnite horizon it along its hangingwall side. The southwestern end of B Lode passes beyond the GQH and continues as a well-mineralised position for several tens of metres of strike, before merging with the B Lode Horizon.

The Western and Centenary Mineralisation probably represent the northeastern continuation of the main development of the Siliceous orebodies.

BL is the largest Siliceous orebody and is the only one of this southwestern group of smaller orebodies to have stratigraphic continuity throughout the Pasminco Mine. It lies at or near the top of the GQH, is strongly banded and stratified and there are a series of smaller sulphide lenses develop in the footwall and hangingwall of the main body of BL.

#### **4.8.5. Relationships between the Siliceous and Calcitic Orebodies.**

Apart from the obvious mineralogical and wall rock differences, there is also a variance in the general trend of the Siliceous and Calcitic orebodies that may be several

degrees of strike. The overlying Siliceous orebodies and their host GQH seems to have a slightly more westerly strike than the Calcitic orebodies and the two elongate packages of mineralisation tend to separate to the northeast. The divergence is particularly obvious between ALL (WAL) and 2L when viewed in plan (Figures 4.2 and 4.3). The divergence reaches its greatest extent in the centre of the mining field, where the Western Mineralisation is laterally separated from 2L and 3L by over 800 metres of Lode Sequence. This divergent relationship has been preserved throughout D2 folding and D3 shearing.

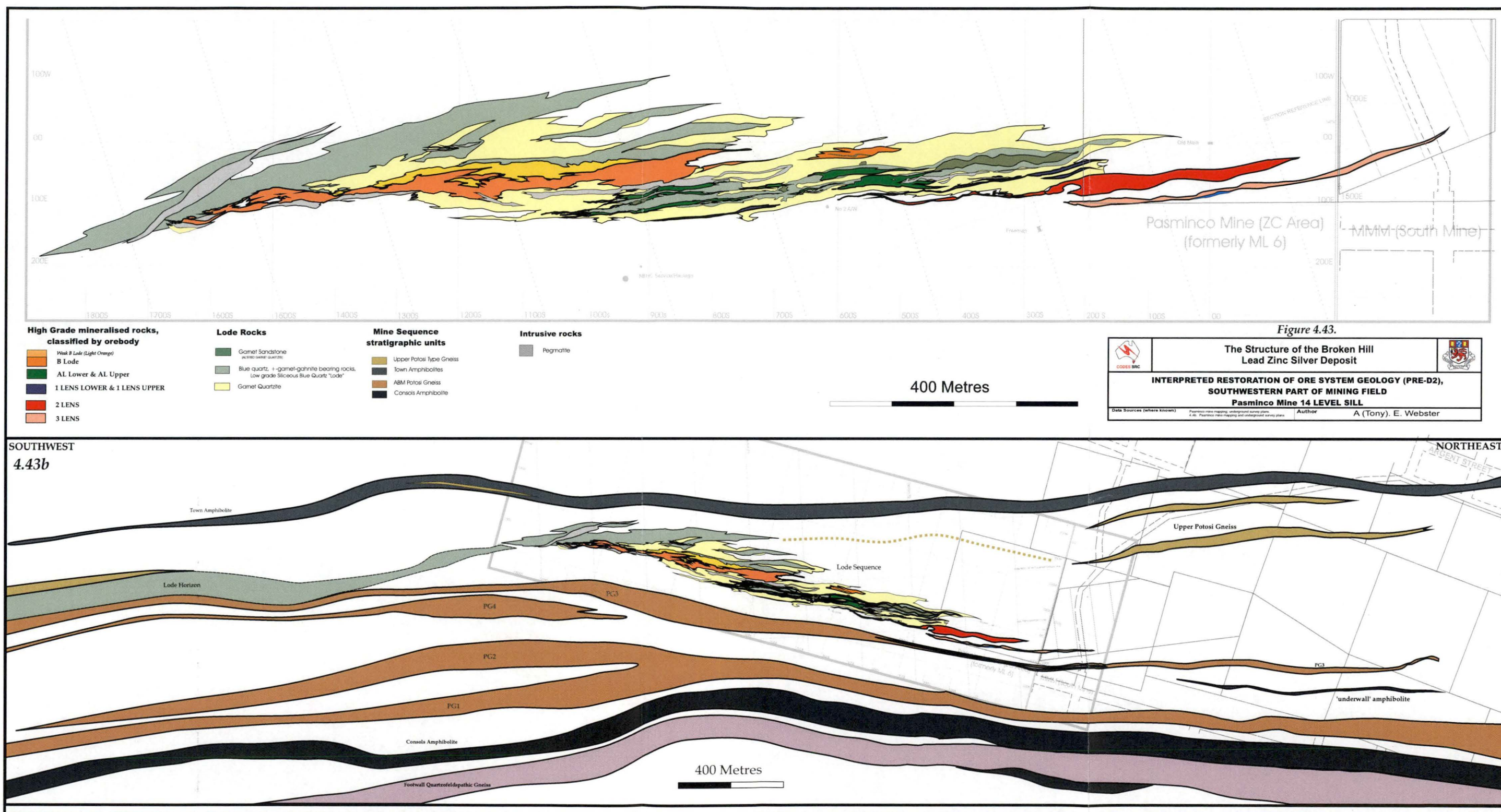
## 4.9. STRATIGRAPHIC SETTING OF THE BROKEN HILL DEPOSIT

### 4.9.1. Environmental Setting of the Broken Hill Orebodies

In this Chapter, data has been presented that shows that the Broken Hill orebodies are a stratified complex of sulphide-silicate-carbonate rocks, manganiferous garnet-rich rocks of various types and textures and minor associated elements such as calc-silicate ellipsoid and banded layers, magnetite-bearing metasediments and thin "banded iron formation". The stratigraphy of the mineralised complex is tectonically modified but the layered succession can still be readily discerned and it can be shown that the mineralised system is virtually intact. Analysis of the available information shows that the stratified orebodies and their associated 'lode rocks' are concordant with the surrounding stratigraphy (Figure 4.43).

Analysis of the relationships between the mineralised complex and the surrounding metasedimentary succession has provided insights into the stratigraphic setting of the deposit. The mineralised complex is located at the southwestern tapered margin of a complex of basic and acid volcanics, with associated intrusives, that is now represented by amphibolites, quartzofeldspathic "granite" gneiss, Potosi gneiss and their interlayered metasediments. The Potosi type gneiss has been shown to be volcanic in origin and the Footwall Quartzofeldspathic Gneiss has been suggested to be at least partly volcanic (e.g. Stevens et al., 1998), as have the amphibolites in the same part of the sequence (e.g. Phillips et al., 1985). The volcano-sedimentary package is lenticular in form and the orebodies lie at the southwestern end of the complex, where it thins significantly to a series of relatively narrow acid and basic units that occupy the southern side of the mining field (Figure 4.1). These units are further reduced in thickness in the immediate footwall of 2L and 3L, where they form a part of





**Figure 4.43.** Pre-D2 restoration of the Broken Hill mineralised system at the southwestern end of deposit (Pasmaingo Mine), in a position approximating the 14 Level. **4.43b** shows the same restoration of the mineralised system but placed into its stratigraphic context within the Mine Sequence stratigraphy. This figure shows the Lode Sequence rotated approximately 30° so that the Mine Sequence Stratigraphy lies parallel to the map boundaries. Refer also to map NBH14 in Appendix 1.

the "underwall zone" of the Footwall Succession. The ABM Potosi Type Quartzofeldspathic Gneiss represents the footwall to the mineralised zone and the Upper Potosi Type Quartzofeldspathic Gneiss grades into spotted psammopelite of the B Lode Horizon in the mines area (Haydon and McConachy, 1987).

The thickened central core of the complex is elongate and lenticular in form and its high aspect ratio is closely analogous to the ribbon-like form of the multiple ore lenses and Lode Sequence strata of the BH orebodies (Figure 4.43b, compare with Figures 4.1, 4.2 and 4.3). On the north-eastern margin of the 'volcanic complex', the orebodies are located in a metasedimentary package that is 'draped' along the north-eastern 'shoulder' of a thickened, lens-shaped development of the ABMPG; a unit interpreted to be volcanic in origin (e.g. Stevens et al., 1998). The mineralised system at Broken Hill appears to wax and wane in concert with the development of the thickened, multi-layered zone in the ABMPG, particularly to the south of the Pasminco mine.

The quartzofeldspathic/mafic complex stratigraphy underlies the mining field and undergoes some remarkable changes in the near ore 'underwall zone'. Apart from the FQG, the key units within it are dramatically thinner in the footwall of the deposit and the distinction between the otherwise diverse lithologies, such as Potosi gneiss, amphibolite, magnetite-bearing pelite and calc-silicate ellipsoid horizons, is diminished and they may be intercalated, or merge into one another (Figure 4.2, 4.3 and 4.9).

The BH orebodies are located within a unique setting within the Willyama Supergroup in the exposed BH Domain. They lie at the southwest end of a quartzofeldspathic/mafic complex that is possibly a metamorphosed volcanic complex, now represented by the Footwall Quartzofeldspathic Gneiss, Consols Amphibolites and ABM Potosi Gneiss, with their associated BIF and calc-silicate horizons. In the near-ore position, the complex is represented by the 'underwall zone', a marked thinning of key marker horizons of the Footwall Sequence.

The BH MinSeq is interpreted to occur in the upper portion of a volcano-sedimentary complex that is now represented by the Footwall Quartzofeldspathic Gneiss, the Consols Amphibolites, the ABM Potosi Type Gneiss and the unusual components of the 'underwall zone'. This complex developed at the regionally significant transition between predominantly feldspathic rocks (composite gneisses) to the more pelitic

facies of the upper Willyama Supergroup (Stevens et al., 1983). The extensive package of basic and acid volcanics, volcano-sedimentary associates and probable chemical sediments is unique within the outcrop area of the Willyama Supergroup and is possibly a stratigraphic guide to the location of the deposit. If it is assumed that the large thickened region of the Footwall Quartzofeldspathic Gneiss to the northeast of Broken Hill is the eruptive centre, then the orebodies formed in a distal position to an eruptive centre. The development of such a package of quartzofeldspathic and basic rocks is possibly unique within the Willyama Supergroup. The stratigraphic association between the Broken Hill orebodies and this unique part of the Willyama Supergroup is an important field association that has exploration significance.

This interpretation offers a more satisfying explanation of the geological environment of the BH orebodies because it places the deposit spatially in association with a major phase of volcanic activity that also marks the transition from the Thackaringa Group to Broken Hill Group.

#### **4.9.2.        Suggestions for Future Research.**

The unique stratigraphic setting of the BH orebodies is worthy of further detailed study. An investigation of the 'volcanic complex' to the south of the mining field and represented by the Footwall Quartzofeldspathic Gneiss, Consols Amphibolites, and ABM Potosi Type Quartzofeldspathic Gneiss is warranted. The research should focus on the units as a package, rather than as individual components of a number of separate groups and units.

Serious consideration should be given to revising the stratigraphic nomenclature of the contact of the Broken Hill Group and the Thackaringa Group and placing the amphibolites, ABM Potosi Type Gneiss and Footwall Quartzofeldspathic Gneiss into the same unit of the Broken Hill Group.



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## CHAPTER 5: STRUCTURE OF THE MINING FIELD

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### 5.1. INTRODUCTION.

The Broken Hill lead, zinc, silver deposit is located within an upper amphibolite to granulite facies gneiss terrane that has undergone multiple deformations (e.g. Laing et al., 1978). Yet, to the author's knowledge, there have been few studies of the gneissic rocks of the mining field that have applied the techniques of structural analysis of high-grade gneiss terrains (Hobbs, et al., 1976; Passchier, et. al., 1990). Hodgson (1967) and Webster (1993; 1994a) are possible exceptions. Yet the sulphide-silicate-carbonate rocks of the deposit, including the companion lithologies ('lode rocks'), gneisses, amphibolites and the intrusives that surround them, lend themselves well to this style of structural studies because of their mineralogical diversity, coarse grain-size and because of the presence of several distinctive and persistent wall-rock marker units (Figure 4.1; Figure 5.1, both contained in separate map folder).

This chapter discusses the results of the application of such techniques to the Broken Hill (BH) orebodies. The characteristics of each of the deformations to have recognisable effects in the mineralised system are described and a structural history of the orebodies is suggested. The basis of the present reinterpretation of the structure of the orebodies is a comprehensive set of mapping-based plans (and sections) compiled for all major levels through the deposit. A complete set of these plans is included in pdf format, as Appendix 1, in the pocket at the rear of this thesis. Two versions of each map are presented; a base geological map and an 'overlay' version showing the key fold and shear structures. Specific examples of key areas are discussed in the text.

A single researcher could never hope to examine a deposit of the size and mining antiquity of BH without utilizing existing data of a variety of forms and formats. Eighty percent of the underground workings are inaccessible and shallow parts of the workings have been mined away by open cuts. So to gain a detailed understanding of the geological architecture of this immense mineralised system, the extensive mine archives were examined in detail. These data allowed a deposit-scale stratigraphic and

structural compilation to be achieved and the geological model developed provided a context for new observations in accessible workings.

5.1.1.           Orientations.

The BH orebodies trend approximately northeast - southwest. It is common in all mines at Broken Hill to refer to directions in reference to mine grids that are oriented approximately parallel to the strike of the lodes. Therefore, mine grid 'east' generally refers to map grid southeast. Throughout this thesis, all references to direction will be to map grid, hence the Pasminco mine lies at the southwestern end of the mining field and not the southern end as it is referred to in mine grid.

5.1.2.           Nomenclature.

Throughout this thesis, a 'standard' form of annotation (e.g. Hobbs et. al., 1976) is used for the structural events, features and fabrics that have been identified and defined within the orebodies and MinSeq. Subscript number represents the chronological order; hence, 'D<sub>2</sub>' follows D<sub>1</sub>. A subscript number followed by a letter (e.g. 'A' or 'B') defines a stage within the event (e.g. D<sub>3B</sub> is distinct but related later stage of D<sub>3</sub>. The codes used are outlined in (Figure 5.2).

*Figure 5.2. Summary table showing the annotation system used in this thesis for deformational events and their related features.*

TERMINOLOGY AND ANNOTATION		
Deformational event    ('D')		
D <sub>1</sub>	First period of deformation	Olarian
D <sub>2</sub>	Second period of deformation	Olarian
D <sub>3A</sub>	Third deformation high grade	Olarian
D <sub>3B</sub>	Third deformation – low grade	Olarian
D <sub>4A</sub>	Fourth deformation	Delamerian
D <sub>4B</sub>	Fourth deformation	Delamerian
Folds    ('F')		
F <sub>1</sub>	Folds formed during D1	
F <sub>2</sub>	Folds formed during D2	
F <sub>3</sub>	Folds formed during D3	
F <sub>4</sub>	Folds formed during D4	
Structural surfaces    ('S')		
S <sub>0</sub>	Pre-deformation layering (mostly bedding)	
S <sub>1</sub>	Foliations formed during D1	
S <sub>2</sub>	Foliations formed during D2	
S <sub>3</sub>	Foliations formed during D3	
S <sub>4</sub>	Foliations formed during D4	

### 5.1.3. Naming of Folds.

The following naming conventions have been adopted in this study.

Localised parasitic folds that are significant at orebody and mine scales within the orebodies are allocated names based on the important historic mine in which the larger part of the strike length of the structure occurs.

Macroscopic folds of more regional significance have not been described in this study. However, the nature of some important and previously described folds is questioned, or their nature and geometry reinterpreted. In such cases, previous names are retained and modified descriptions are presented.

All major mine-scale fold axial traces are shown on the structural interpretation version of each geological map presented in Appendix 1 (in the rear pocket). Plunge direction and fold names are also shown. The information is shown in a dedicated layer in the digital files (Corel Draw v7 format). View the "structure" layer by using the 'layer manager' facility.

### 5.1.4. Naming of Shears and Faults.

Geological structures are referred to constantly on the mines; particularly shears and faults that have ground support ramifications. Therefore, the terminology in common use can differ from that in many published papers and monographs. This variance is partly because the geological terminology is used in the mines on a day-to-day basis and evolves over many years of constant geological investigation. Published terminology remains static and is often not suitable for mine use. Therefore, wherever possible, the terminology of shears and faults that were, or are in use in the mines (especially the Pasminco and North Mines) will be used in preference to those discussed in published sources. Existing names (either published, in company reports or in general usage by Mine Geology Departments) are retained where possible and modified or redefined as required. However, there have been many newly recognised or re-defined structures and these are named using a similar convention to that for folds.

The trace of significant high-grade shear planes/belts of transposition, and fault planes are shown on the structural interpretation version of each digital geological map presented in Appendix 1.

## 5.2. METHODS

Underground geological mapping is particularly applicable to the study of deformed orebodies in gneiss terranes because the geological features recorded are also useful for structural geological interpretations. 'Backs' mapping provides a horizontal slice through any dipping geological surface, thus providing exposures that are accurate strike measurements. Underground openings (drives, stopes, rises, winzes) are very accurately located and their position within three-dimensional space is surveyed to a high degree of accuracy. Underground development is also systematically laid out, often in a regular symmetric pattern. Therefore, 'backs' (the 'ceiling' of an underground drive) mapping provides outcrop maps that are regularly spaced and the position of those 'outcrops' relative to each other is well defined. Underground development provides the perfect situation for generating form surface and lithological maps of high-grade gneiss packages from 'outcrop' exposures because the 'outcrops' are at exactly the same level and arranged in a regular layout, rather than the serendipitous occurrences of outcrops in natural surface exposures. Underground development also has the added benefit of being constructed at successive levels within the same rock units so 'stacked' sequences of horizontal form surface and lithological maps can be constructed at successive levels through the gneissic rock units. This adds a third dimension to the structural analysis of the gneiss package.

Details of the methods utilised to complete this structural analysis are presented in Appendix 6. Additional information about the methods used to complete this study is presented in Appendix 3.

## 5.3. TIMING OF DEFORMATION

Recent SHRIMP U-Pb zircon dating of key lithologies in the Willyama Supergroup has placed time constraints on the deformational history of the Broken Hill Domain and is summarised and discussed by Stevens et al., (2000) (Figure 5.3).

**Figure 5.3.** Age constraints of regional metamorphic events identified in the Broken Hill region by Stevens et al., (2000). This table shows the slightly different interpretation of the structural history of the Broken Hill Domain of G. Gibson (GMG) and B Stevens (BPJS) and their shared positions.

TIMING OF DEFORMATION			
Late granite ages	Shared position	BPJS	GMG
<b>1580±5 Ma</b> Dacite dyke intruding Bijerkerno Metasediments.	post-D3	post-D3	post-D3
<b>1591±5 Ma</b> Post-D3 Mundi intrusion	post-D3	post-D3	post-D3
<b>1596 ±3 Ma</b> Cusin Creek pluton	<><><>< <b>D3</b>	post-D2 pre- or syn-D3	post-D2 pre- or syn-D3
<b>1597±3 Ma</b> ‘Lf’ granite on the Purnamoota Road	<><><>< <b>D2</b> (main fabric in granitic gneisses, etc.)	predates D1	probably <b>syn-D2</b> , (but maybe pre-D2)
<b>-1600 Ma</b> Metamorphic zircon rim overgrowths			

The lack of zircon with metamorphic characteristics before 1600 Ma suggests no high-grade metamorphism took place before 1600 Ma. Zircon with metamorphic character has only been detected between 1600-1590 Ma. Igneous/detrital zircon grains 1690 Ma or older, are plentiful, yet no pre-1600 Ma metamorphic grains have survived. The ages and features of intrusive rocks constrain regional D3 deformation and possibly D1 and D2 to between 1597±3 and 1591±5 Ma (Stevens et al., 2000).

#### 5.4. FIRST DEFORMATION (D1)

The earliest structural event defined within the Willyama Supergroup (D1) took place during the Olarian Orogeny (Laing et al., 1978; Webster, 1994a; White et al., 1995) and reached granulite grade (e.g. Laing et al, 1978; Stevens; 1986). The event has been variously interpreted to produce regional nappes and nappe-thrusts with significant overturning (Laing et al., 1978; Marjoribanks et. al., 1980), or the development of a fold and thrust belt that following a prolonged Olarian thrust event (White et al., 1995).

No F1 folds have been identified in the BH region (e.g. Hopwood 1976; Laing et al., 1978; White et al., 1995) and D1 has left few effects in the rocks of the mines area. The following discussion deals only with the aspects of D1 within the orebodies and immediate wall rocks that were observed during this study (summarised in Figure 5.4). For details of the various interpretations of the regional D1 event, refer to Laing et al., (1978); Marjoribanks et al., (1980), White et al., (1995), Gibson (2000b) and Stevens (2000).

*Figure 5.4. Summary of the main effects of D1 within the rocks of the Broken Hill mineralised system and Mine Sequence. Each of these features is discussed in detail in the following sections.*

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**Main features of D1 in the Broken Hill Mining Field  
(OLARIAN OROGENY)**

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**Pegmatite intrudes Lode Sequence:**

- Separation pegmatites, in Garnet Quartzite Horizon at the southwest end of mining field.  
*S1 banding in lode pegmatite?*
- Widespread stratiform dykes at margins of psammite & quartzofeldspathic units in the northern leases
- Bedding parallel & stratiform melt segregations in clastic metasediment, especially at the margins of pelitic & psammitic layers.

**Biotite-sillimanite foliation (S1), parallel to bedding in MinSeq metasediments.**

Bedding parallel sillimanite-biotite foliation (S1 of Laing et al., 1978).

Coarse knots & bundles of fibrous sillimanite developed in pelites in the northeast region (wrap pyrite in places).

**Early structural/metamorphic features of the ore lenses (pre-or syn-D1)**

Isochemical metamorphism, annealing & grainsize coarsening in orebody sulphides & gangue.

**Calcitic Orebodies**

- Pegmatites in 2 Lens.

**Siliceous orebodies**

- Pegmatites in B Lode & in the zones between B Lode & underlying A Lodes.
- 

#### **5.4.1. 'Bedding-parallel' Foliation Defined by Biotite-Sillimanite (fibrolite).**

D1 produced few recognisable effects within the orebodies and wall rocks. The most commonplace and pervasive evidence for D1 in the mines area is a sporadically

developed, bedding and contact parallel schistosity defined by biotite and fibrolite (S1). It is developed within pelitic and psammopelitic rocks but is rarely found within garnet quartzite (usually at contact zones with clastic metasediments) and blue quartz lode rocks.

S1 is defined by oriented planar aggregates of sillimanite, fibrolite and by preferred orientation of sillimanite needles and biotite laths. Garnet and orthoclase porphyroblasts are also developed elongate parallel to the foliation (Laing et al., 1978). Within quartzofeldspathic gneisses, S1 is a metamorphic segregation of alternating quartzofeldspathic and mafic laminae up to 1cm thick. Biotite, muscovite and sillimanite may also be constituents of the laminae where present. Amphibolites show a generally finer differentiated fabric and oriented hornblende and biotite laths. Sillimanite and fibrolite define a prominent lineation within S1 in pelitic rocks (Laing et al., 1978). Magnetite banding is also a component of the foliation in amphibolites beneath 3L in the Pasminco Mine. No F1 folds with an S1 axial plan surface have been identified (Laing et al., 1978). S1 is poorly developed in the rocks adjacent to 2 Lens in the Pasminco mine because they are generally of psammitic composition.

In the northern leases of the Pasminco mine, S1 developed within pelite often contains abundant, coarse, knotted to lenticular bundles of fibrolite. This feature is rarely seen in the Pasminco Mine or southern leases and may result from slight differences in composition, slight local variation in the metamorphic grade at the northern end of the deposit, or reflect the apparent greater abundance of pelitic rocks within the MinSeq. Psammitic rocks on the northern leases are also relatively enriched in fibrolite compared to the southern leases.

#### 5.4.1.1. *Sillimanite pressure shadows on cubic pyrite crystals.*

Pre-D1 cubic pyrite crystals were observed in outcrop in a locality just southwest of Piesse's Nob. The well-formed cubic crystals (goethitised in outcrop) are located within a narrow interval in the Lode Horizon comprising a linear outcrop of psammite and pelite. The outcrop consists of a deformed sequence of coarse-grained pelite with intercalated bands of very fine-grained, garnet-bearing psammite up to 1.5m wide. Pyrite occurs as perfectly formed cubic crystals in both psammitic and pelitic layers, with the largest crystals being scattered through the pelite (range, 1mm to 8mm). The

crystals in psammite layers are smaller and more widely dispersed. The whole occurrence forms a distinct, vaguely defined 'horizon'.

Many cubic pyrite crystals are draped by the S1 fibrolite-biotite foliation and show no sign of distortion. The fibrolite forms white symmetrical tails that taper off to ragged ends with distance from the pyrite crystal it enshrouds. This produces a 'flame shape' or 'comet tail'-like appearance. Such fibrolite tails can be present on both sides of a cube or on a single side and parallel a sillimanite-defined lineation (stretching lineation?). Fibrolite tails are not present on every pyrite crystal and may have been formed along shear-related foliation planes that pass through the psammite and encounter pre-existing pyrite crystals

It is probable that this pyrite occurrence is pre-D1 because strongly developed fibrolite 'bundles' did not form during later structural events and the S2 fabric crenulates S1 fibrolite bundles (e.g. Laing et al. 1978). This small occurrence of early pyrite crystals suggests that there has been very little bedding parallel transposition within the Lode Horizon (Hobbs, 1966), at least in this one locality that is distant from the main orebody position.

#### **5.4.2. D1 Pegmatite.**

Pegmatite dykes and melt segregations were widely developed in the MinSeq metasediments early in its metamorphic history and are interpreted to have formed during early D1. While not strictly a structural fabric, their occurrence throughout the MinSeq is the most widespread effect of D1 in the Lode Sequence, orebodies and in the proximal Lode Horizon (LH). Pegmatite occurrences in the Lode Sequence have been described in detail by Haydon (1983).

A distinctive variety of pegmatite, known locally as 'lode pegmatite', is a characteristic component of the Lode Sequence and consists of a medium to coarse-grained quartzofeldspathic rock composed of K-feldspar, plagioclase and quartz with minor garnet and biotite. They have a close spatial association with the ore lenses (Haydon and McConachy, 1987) and the B Lode Horizon (BLH) in the Pasminco Mine.

Green feldspar pegmatite (plumbian orthoclase) was formed within lode pegmatite during D1 and is characteristic of this event (Figure 5.5). It is best developed where



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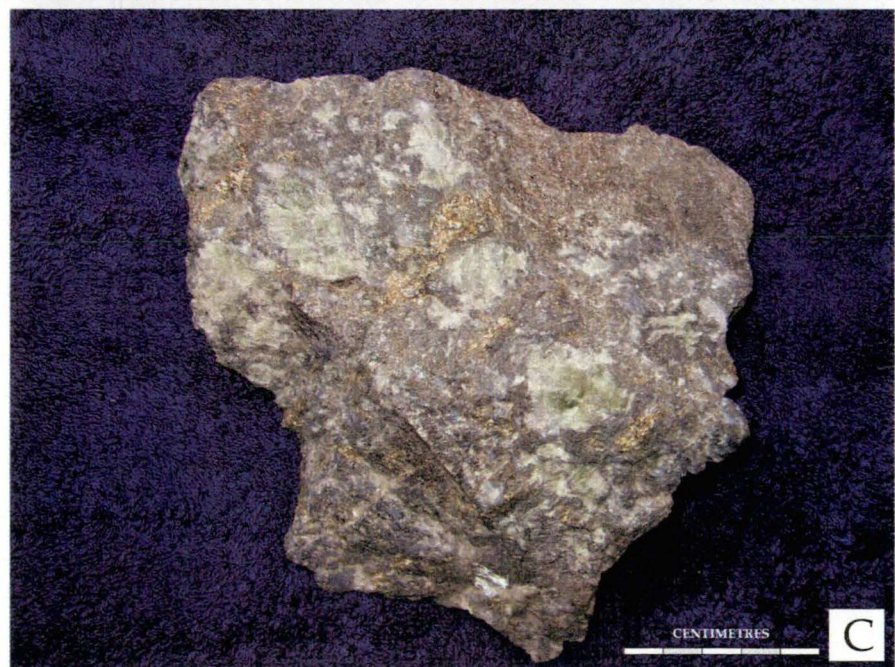
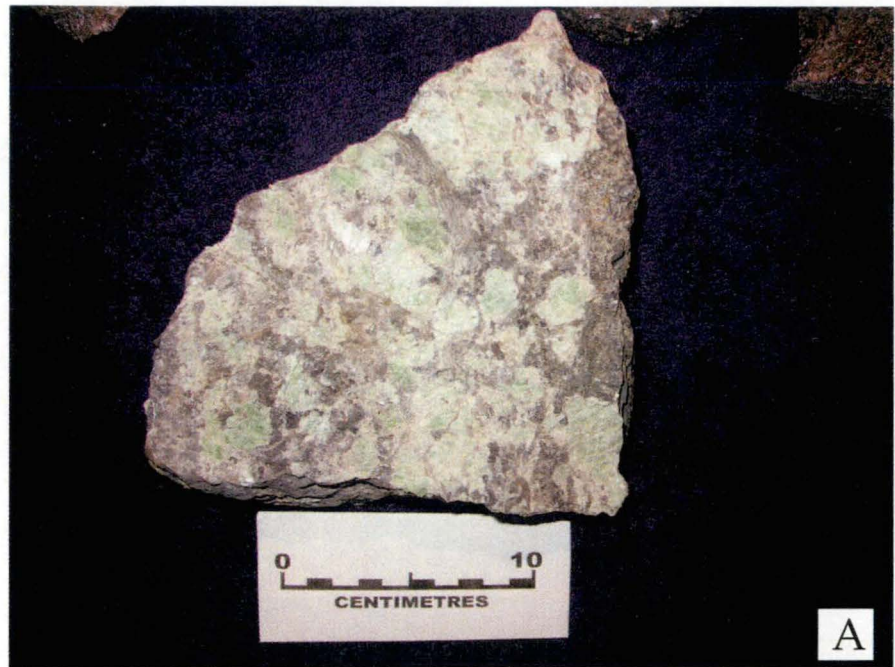


Figure 5.5.

pegmatite intrudes mineralisation, especially at the zones of contact between sulphides and pegmatite. Green feldspar was altered to grey feldspar, impregnated by very fine-grained aggregates of galena and quartz and brecciated by siliceous veining during D2 and probably D3.

A coarse compositional layering, defined by feldspar grain size and biotite abundance, is observed in many large lode pegmatite bodies and generally parallels the contacts (e.g. on the 8 Level of the Pasminco Mine, near the junction point with the Surface Decline). The banding may be a differentiation fabric formed during crystallisation, or it may be an S1 metamorphic fabric.

Large and relatively tabular bodies of stratiform to mildly transgressive lode pegmatite intruded the hangingwall of the Lode Sequence within the area of Pasminco Mine during D1, particularly in the hangingwall of the Garnet Quartzite Horizon (GQH) and within the BLH. Pegmatite is largely stratabound within the Lode Sequence and focussed along the northwestern contact of the GQH with extensive intrusions into B Lode (BL). Smaller bodies of pegmatite lie within the garnet quartzite and low-grade siliceous mineralisation between BL and A Lode Lower and are known as the 'separation pegmatite's' by mine geologists. Narrow bands (generally < 1m) of pegmatite were also intruded into the upper contact of 2L (Webster 1993, 1994a) and into the footwall region of BL. Pegmatite segregations are also observed in A Lode Lower, and dismembered fragments of pegmatite have been recorded in 3L as feldspar gangue.

D1 pegmatite dykes on the northwestern margin of the BLH are transgressive of the stratigraphic contacts with the GQH and the orebody contacts. Detailed plan interpretations show that pegmatite dykes are transgressive of the stratigraphy of the GQH orebodies, including ore-garnet quartzite contacts, silicified margins of orebodies and the occasional bands of psammopelite, psammite and pelite that occur within the garnet quartzite masses. B Lode is also extensively intruded by pegmatite (e.g. see map NBH17 in Appendix 1). The dykes intruded after the stratigraphy and linearity of the GQH and BLH was established. So, if the linearity and complex stratification of the orebodies and GQH was the result of D1 tectonism (i.e. the mineralisation was emplaced by a syn-metamorphic epigenetic process or severely attenuated during D1), then the deformation that produced this linearity must have been completed prior to pegmatite intrusion. If the orebodies were formed at the peak of regional

metamorphism, as has recently been suggested by Ehlers et al (1996) then pegmatite formation must have formed post-peak of metamorphism and post extension, which is unlikely, based on outcrop relationships.

Lode pegmatite bodies within the BLH, GQH and throughout the Lode Sequence and Lode Horizon were folded, invaded by mobilised sulphides and strongly metasomatised during D2. Dismembered pods of lode pegmatite are rimmed by syn-D2 wollastonite, hedenbergite and bustamite in 2L (Webster 1994a) and stratiform pegmatites occur within B Lode.

#### 5.4.2.1. *Timing of Pegmatite Intrusion.*

The lode pegmatites and 'separation pegmatites' within the Pasminco Mine have been folded by D2 folds in some areas (e.g. Figure 4.11 and refer to map NBH15 in Appendix 1). Detailed plan interpretations on successive mine levels show that the pegmatites are transgressive of the stratigraphy of the orebodies hosted within the Lode Sequence, including ore-garnet quartzite contacts, silicified margins of orebodies and the occasional bands of psammopelite, pelite and psammite that are intercalated with the garnet quartzite. These transgressive relationships have been deformed by F2 folding, thus showing that pegmatites intruded the GQH and B Lode Horizon prior to D2 (see below). The spatial relationship between ALL, ALU and BL and their surrounding stratigraphy were established before pegmatite formation.

Major pegmatite bodies are slightly more shallowly 'northwest' dipping than are the orebodies (especially BL) and crosscut the mineralisation. On the 14 Level of the Pasminco Mine, they occur to the southeast of BL. They cross this orebody at approximately the 15 Level and occur on the western side of the mineralisation from the 16-17 Levels (refer to maps NBH14 to NBH17 in Appendix 1). The transgressive nature of the dip of the lode pegmatite bodies has been partly obscured by F2 folding. Therefore, the lode pegmatites are stratabound within the Lode Sequence but are not truly stratiform and they transgress the GQH and BLH. The compositional banding of lode pegmatites (S1?) is invariably folded by F2 folds. The transgressive nature of many dykes show that these bodies have intruded the MinSeq and make it unlikely that they were formed by *in situ* partial melting of originally stratiform clastic metasedimentary units, as was suggested by Matthias (1974).

Pegmatite dykes have been mineralised during post-D1 alteration events including, silicification (D2/D3A) and muscovite alteration (D3A/B, D4A). Alteration of dykes is particularly focussed where they lie at orebody contacts; especially where strongly developed quartz-muscovite-biotite shearing (D3B, see below) is present. Garnet occurs in quartz veins within altered pegmatite where blue quartz, sulphide and saccharoidal siliceous alteration affect the peripheries of dykes in deformed regions, suggesting that the pegmatites were in place prior to D2/D3A when such alteration was widespread (see below). The close spatial relation of muscovite alteration of the dykes to areas of high D3B and probable D4 strain ties this alteration to these deformations. The alteration of dykes can be quite intense and in the 'southern' B Lode mining area of the 17 and 18 Levels of the Pasminco Mine, blue quartz alteration, silicification and mineralisation of a dyke was so intense that it produced lode-like rocks in some locations. Galena-sphalerite-garnet-quartz veins were formed within the altered pegmatite and green feldspar crystals were altered to grey feldspar with fine-grained galena inclusions, leaving only remnant green cores (Figure 5.5b & c).

#### 5.4.2.2. *Stratiform pegmatitic dykes in the northern leases.*

Stratiform pegmatite bodies are ubiquitous throughout the metasediments of the Lode Horizon and nearby Thackaringa and Sundown Groups on the northern leases of the Pasminco Mine. They form planar sheets (linear on maps and sections) ranging in thickness from sub-centimetre scale, quartzofeldspathic segregation's to large lenticular bodies up to several metres thick and tens of metres in strike length. The abundant stratiform D1 pegmatite of the northeastern part of the deposit is not seen in the Pasminco Mine, or the southern leases at the southwestern end of the field, nor is it apparent in the central region of the mining field. The following discussion focuses mainly on pegmatite occurrences that are associated with the mineralisation in the Lode Horizon near the Potosi and Silver Peak Extended lead-zinc deposits (see section 4.7.11 and Figure 4.42).

In the northern leases, pegmatite lenses and dykes consist of coarse-grained aggregates of K-feldspar (often exhibiting spectacular graphic intergrowths with quartz), quartz and plagioclase. K-feldspar is variably altered to very fine aggregates of D3/D4 saccharoidal quartz and muscovite (pseudomorphing the feldspars). Minor constituents include rounded garnets, white vein quartz, chlorite, biotite clots and gahnite.



In diamond drill core and from outcrop observation, it is observed that major bodies of pegmatite are elongate planar features, lenticular in cross section and are most often well developed on the boundaries of psammitic and/or quartzofeldspathic units where they are in contact with pelites. Stratiform pegmatite distribution mirrors the distribution of stratigraphic units. So, these highly visible units provide an approximate indication of the distribution of stratigraphic horizons (for form-surface/structural interpretation) within relatively monotonous sequences of metasediments during aerial photographic interpretation. Because the intrusions conform to the gross stratigraphic variations of the metasedimentary pile, they are referred to in this study as 'stratiform' pegmatites. The distribution of stratiform pegmatite dykes has been used to interpret details of the structure and stratigraphy in aerial photographic interpretations of the economically important Potosi-Silver Peak-Round Hill area (A. E. Webster, unpublished data).

#### 5.4.2.3. *Shearing of pegmatite dykes.*

Stratiform pegmatite dykes have been disrupted, but in many cases not destroyed, by early (high grade) and late retrograde shearing associated with the Globe-Vauxhall Shear (e.g. Figure 4.1). Pegmatite distribution, being largely controlled by pre-existing stratigraphy has been well preserved in parts of the sequence where earlier fabrics have been destroyed by retrogression. Sheared stratiform pegmatite's are the best-preserved indicator of the pre-shearing sedimentary stratigraphy.

#### 5.4.2.4. *Pegmatite and Mineralisation.*

All pegmatite's in the Potosi-Silver peak area are extensively silicified and muscovite altered. Alteration diminishes inwards from the edges in larger pegmatite bodies while thinner dykes and quartzo-feldspathic segregation's are usually completely altered. Alteration often results in the complete replacement of K-feldspar with fine-grained aggregates of quartz and muscovite. Occasionally there are less-altered feldspar cores preserved in the centres of larger crystals. Where silicification is most intense, the pegmatite's can be completely replaced by vein quartz, partly by processes of brecciation and/or veining. Intensely altered K-feldspars are commonly cut by fine networks of hairline fractures. Such fractures are filled with translucent to clear vein quartz. These fractures are sometimes spatially associated with larger quartz veins.

Mafic phases within the silicified pegmatite included biotite clots and spots, streaks and large rounded garnet porphyroblasts. The garnet and biotite are associated with fractured regions of the pegmatite in which quartz veining is prevalent. Mafic minerals are also common within 'xenoliths' of metasedimentary wall rock within the dykes. Garnet porphyroblasts, sillimanite and chlorite are common within, and associated with, these xenoliths. Chloritic alteration of mafic phases is also common and is probably the same age as the muscovite alteration (D3B/D4A). Garnet, biotite and chlorite also occur within siliceous zones between feldspar fragments and along quartz-filled cleavage planes within large K-feldspars.

Several pegmatite dykes immediately south of the Potosi and Silver Hill mines exhibit marginal alteration zones containing 1mm to 1cm sized gahnite crystals ('gahnitisation') within blue quartz alteration.

Stratiform pegmatite dykes and segregations show a close spatial association with mineralisation in the Potosi-Silver Peak Extended area. Sphalerite and galena is often located on the margins of stratiform pegmatite bodies (often in substantial but sub-economic masses) and is very commonly found in small, blue-quartz altered pegmatitic stringers. These occurrences are interpreted to be the result of D2-D3A syntectonic mobilisation. This alteration appears to be associated with D3A (or the onset of retrograde metamorphism). Such sulphides are generally very vein-like and may be enriched in pyrrhotite and chalcopyrite.

Psammitic units also show a similar, though less well developed spatial association with silicification and quartz vein formation.

#### **5.4.3. Sulphide-silicate Gangue Annealing.**

Recrystallisation and grainsize coarsening of sulphides, silicates and calcite within mineralisation resulted in a pervasive 'annealed' texture within all orebodies (equigranular grainsize, triple junctions). Thicker primary banding (S0), defined by variations in silicate, calcite, sulphide, quartz, fluorite or apatite abundance, and stratigraphic variations within the orebody were preserved despite the increase in grainsize. A major example of the preserved S0 within mineralisation is the calcite-sulphide-silicate banding within 2L and the preservation of the rhodonitic layers in 2L,

3L and ALL (Webster 1993, 1994a) (Figures 4.35, 4.36 & section 4.7.1). Annealed banded rocks are intruded by green feldspar-bearing lode pegmatite dykes that are folded with the banding by F2 folds (Webster 1994a; see below).

There is no evidence that any D1 sulphide mobilisation took place within the orebodies. If significant tectonism had been associated with this event, then widespread development of mobilised sulphides and the textural reworking of the sulphide and gangue mineral assemblages should have resulted; as during D2 (see below). However, no such pre-D2 textures are observed in the orebodies and all calc-silicate pyroxenes, pyroxenoids and mobilised sulphides are related to D2 or D3 structures (see below).

No mobilised sulphides zones are folded by D2 and all the studied examples are demonstrably related to sites within the orebodies and nearby rocks that were created during D2 (mainly folding) or later events.

#### **5.4.4. Overturning of the Mine Sequence in the Mines Area.**

The MinSeq in the mine lease area is interpreted to lie on the overturned limb of an isoclinal D1 nappe and the orebodies and the encompassing MinSeq was considered to be inverted by Laing et al. (1978). The evidence cited in support of this view includes the metal zonation within the orebodies (Stanton and Richards 1961), which was interpreted to be in the reversed order of what would be expected in a typical base metal deposit. The limited scope of the investigations used in that work and the complex orebody geometry, structure and the effects of syntectonic sulphide mobilisation in the orebodies make the conclusions based on metal distribution studies unreliable. Such patterns require re-examination, in the light of the structural and stratigraphic outcomes of this study. Also, the evidence for overturning of the mine area drawn from metal zonation studies (Stanton and Richards 1961) is too dependent on the assumption that the BH orebodies were formed by vulcanogenic processes, a theory for which little corroborative data is available and which cannot be conclusively demonstrated from the observed geology of the deposit.

Younging data obtained from graded bedding identified by Laing et al (1978) provided the most convincing argument for overturning of the mines area. However, the younging data provided by them, while not disputed, is ambiguous and open to



alternative interpretations that support the northward facing model (Figure 5.6a & 5.5b). They also interpreted their data on the basis that the major folds affecting the orebodies and Lode Sequence were F3, but these folds have since been shown to be prograde F2 (two-pyroxene grade) and not retrograde (Webster 1993, 1994a, 1994b; this study). Local reversals of graded bed facings within the MinSeq are probably related to parasitic F2 folding of the same style as those in the Lode Sequence and orebodies and not to a major regional F2 "Broken Hill Antiform" or "slide". Laing et al's., (1978) placement of this structure is also shown in the Figure 5.6a and b.

As stated in Chapter 4, for the purposes of this study, the MinSeq is considered the right way up and northward facing.

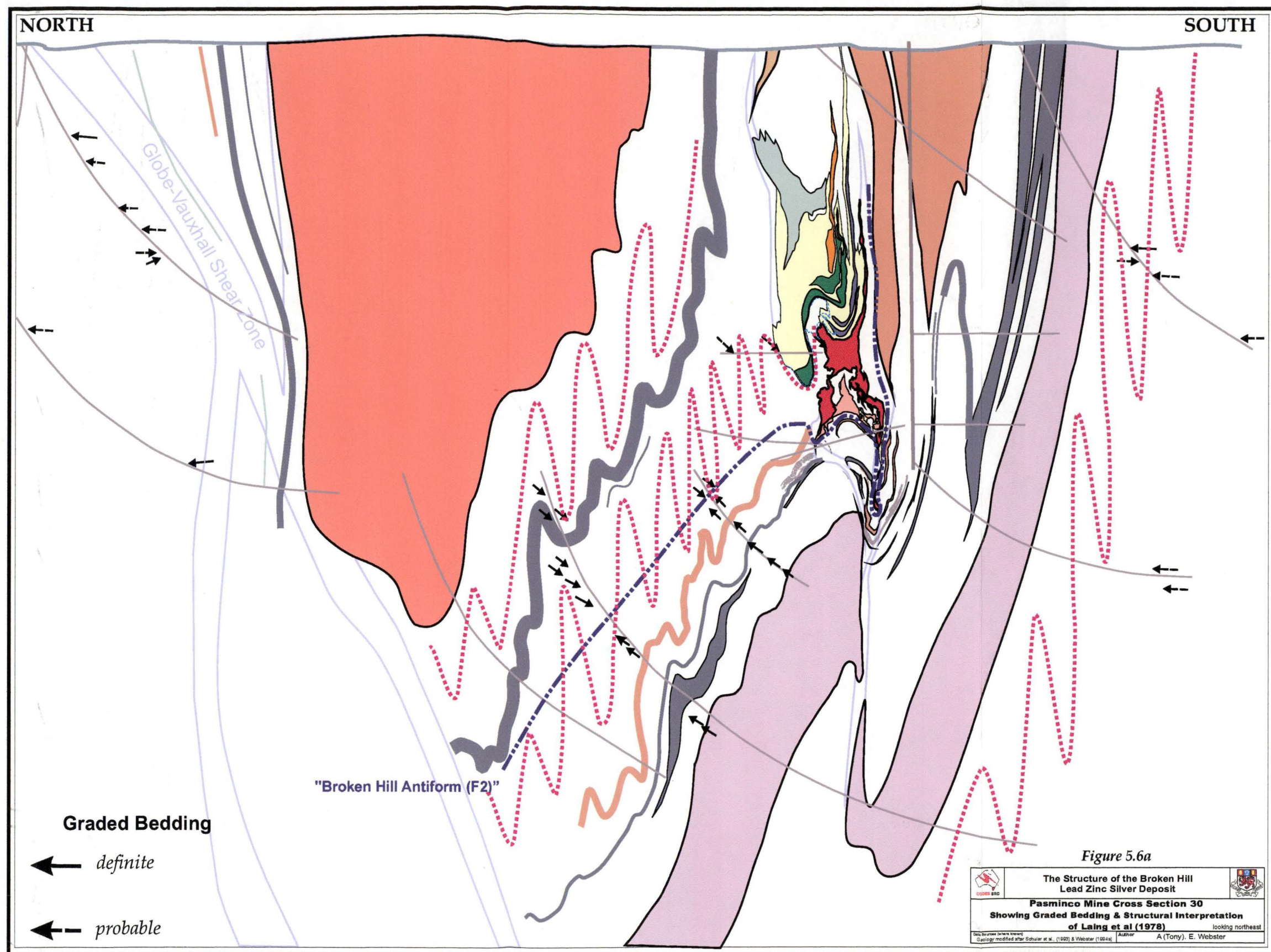
#### 5.4.5. D1 "Slide".

A recent three-dimensional model of the Broken Hill Domain has been generated by the Predictive Mineral Discovery CRC, based at Melbourne University. The model depicts a "D1 slide" below the orebody that is located approximately along the BIF-magnetite-bearing pelite horizon of the 'underwall zone' (see Chapter 4). The structure is depicted as deformed by the upright F2 folding that has affected the orebodies (see section 5.5.2.1).

The evidence for this interpreted possible structure (stated to still require validation) includes the following (R. C. Haydon, pers comm. October 2002):

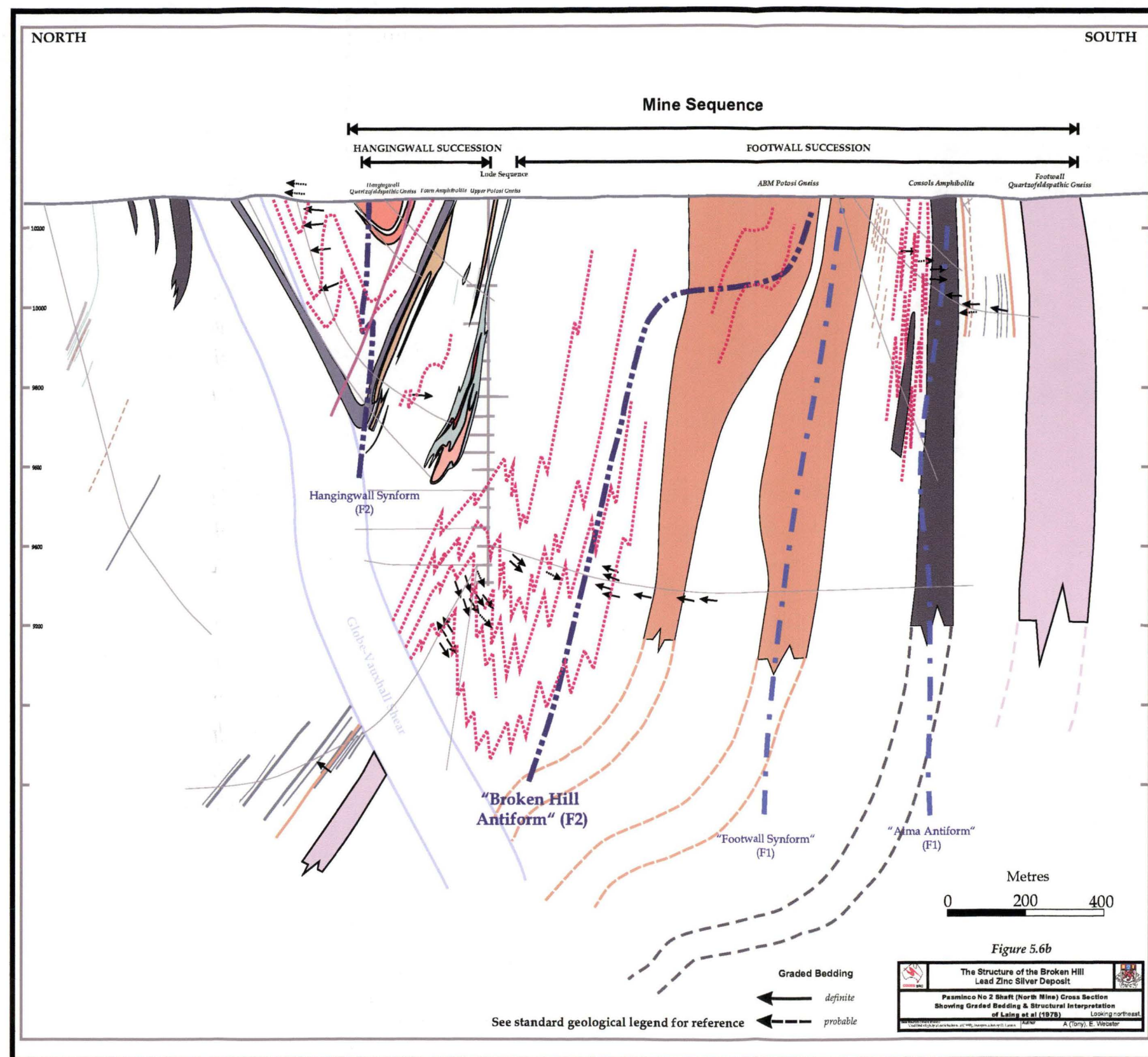
1. There is a sharp break in the geochemistry [below the orebodies] that is "difficult to explain purely on stratigraphic or alteration grounds",
2. Laing [e.g. Laing et al, 1978)] and many others recorded changes in younging based on graded beds that suggest a discontinuity,
3. There is an abundance of layer parallel high strain zones that occur around the top of the Broken Hill Group,
4. The presence of high strain zones containing abundant magnetite in and around the top of the Broken Hill group (these are not the BIF's),
5. There is possibly some "sequence" missing on some sections, and
6. Probably the most significant issue is that a structural discontinuity seems to be the only way that a self-consistent model that honours all the mapped geology ranging from regional to mine scale can be developed.





**Figure 5.6a.** Freeman Shaft cross section (section 30) showing an alternative interpretation of the facing data of Laing et al (1978). The interpreted general trend of S0 is shown as a pink dotted line. The axis of Laing et al's., (1978) 'Broken Hill Antiform' is shown as a blue dotted line labelled "Broken Hill Antiform (F2)". The facing data can quite easily be explained by a slightly more complex style of F2 folding (similar to that defined in the mineralised system) than that suggested by Laing et al (1978), who based their interpretation of fold style on existing mine sections interpreted from diamond drill core information. Such cross sections are compiled from widely spaced drill hole data and the resultant interpretations can tend to smooth out the geometry of key marker units. The style of F2 folding that is observed in outcrop in this region of the mining field (Figure 5.16) and which is observed in the underground workings of North Mine (e.g. Figures 5.10) supports this interpretation better than the smooth folds originally envisioned by Laing et al., (1978). A "Broken Hill Antiform" is not necessary to explain the facing data. This interpretation shows that the facing data published by Laing et al (1978) can also be used to support a model of F2 folding in the orebodies.





**Figure 5.6b.** No 2 Shaft cross section showing an alternative interpretation of the facing data of Laing et al (1978). The interpreted general trend of S0 are shown as a pink dotted line. The axis of Laing et al's, (1978) 'Broken Hill Antiform' is shown as a blue dotted line labelled "Broken Hill Antiform (F2)". The facing data can quite easily be explained by a slightly more complex style of F2 folding than that suggested by Laing et al (1978), who based their interpretation of fold style on existing mine sections interpreted from diamond drill core information. Such cross sections are compiled from widely spaced drill hole data and the resultant interpretations can tend to smooth out the geometry of key marker units. The style of F2 folding that is observed in outcrop in this region of the mining field (Figure 5.16) and which is observed in the underground workings of North Mine (e.g. Figures 5.10) supports this interpretation better than the smooth folds originally envisioned by Laing et al., (1978). A "Broken Hill Antiform" is not necessary to explain the facing data. This interpretation shows that the facing data published by Laing et al (1978) can also be used to support a model of F2 folding in the orebodies. Axes of "F1" folds interpreted by Laing et al., (1978) are also shown (labelled F1).

There are extensive exposures of this part of the stratigraphy in the Pasminco Mine (e.g. 18, 19 and 20 Levels; Figures 4.9 & 4.37, see also maps NBH17, 18, 19 and 20 in Appendix 1) and extensive diamond drilling has traversed this part of the sequence (e.g. Figures 4.9, 5.6a & b, 5.7). The extensive exposures have not revealed any evidence for such a fundamental shear plane. The entire lower part of the MinSeq stratigraphy, extending from the bottom of 3L to the Footwall Quartzofeldspathic Gneiss, is intact but thinner than the outcrop area to the south of the mining field. The close inter-relationship of persistent layers of amphibolites, magnetite-bearing metasediments, Potosi type gneisses and calc-silicate horizons within this zone (discussed in section 4.3.6) does not support a shear zone. Each of these lithologies may have transitional phases, but the underwall zone has not been dislocated or sheared out by a D1 "slide". Therefore, for the purposes of this study, the "D1 slide" proposed in this position is not accepted. The other lines of evidence are not conclusive. Point 2 is dealt with in section 5.4.4 and was discussed in section 4.6). Point 1 is very weak since the nature and distribution of alteration has never been documented.

## 5.5. SECOND DEFORMATION (D2).

The second deformation to affect the Broken Hill (BH) mines area (D2) was a widespread upright folding event that produced the earliest significant geometric modifications to the orebodies and Lode Sequence. It resulted in folds within the MinSeq at all scales; from sub-metre to mine-scale. D2 was a granulite grade event, so apart from producing geometric changes in the stratigraphy; it is also associated with the development of significant (often extreme) textural changes in the orebodies (Hodgson, 1967; Maiden, 1975; Webster 1993, 1994a & b; this study) that are represented by a diverse range of sulphide and sulphide-silicate vein styles and coarsely-crystalline gangue mineral textures. D2 recrystallisation locally overprints the relatively homogenous D1 annealed fabric of the orebodies as well as the pre-D1 (S0) features of the deposit such as sulphide-silicate-carbonate banding and rhodonite layers (Webster, 1993; 1994a; this study). A summary of the key features of D2 is presented in Figure 5.8.



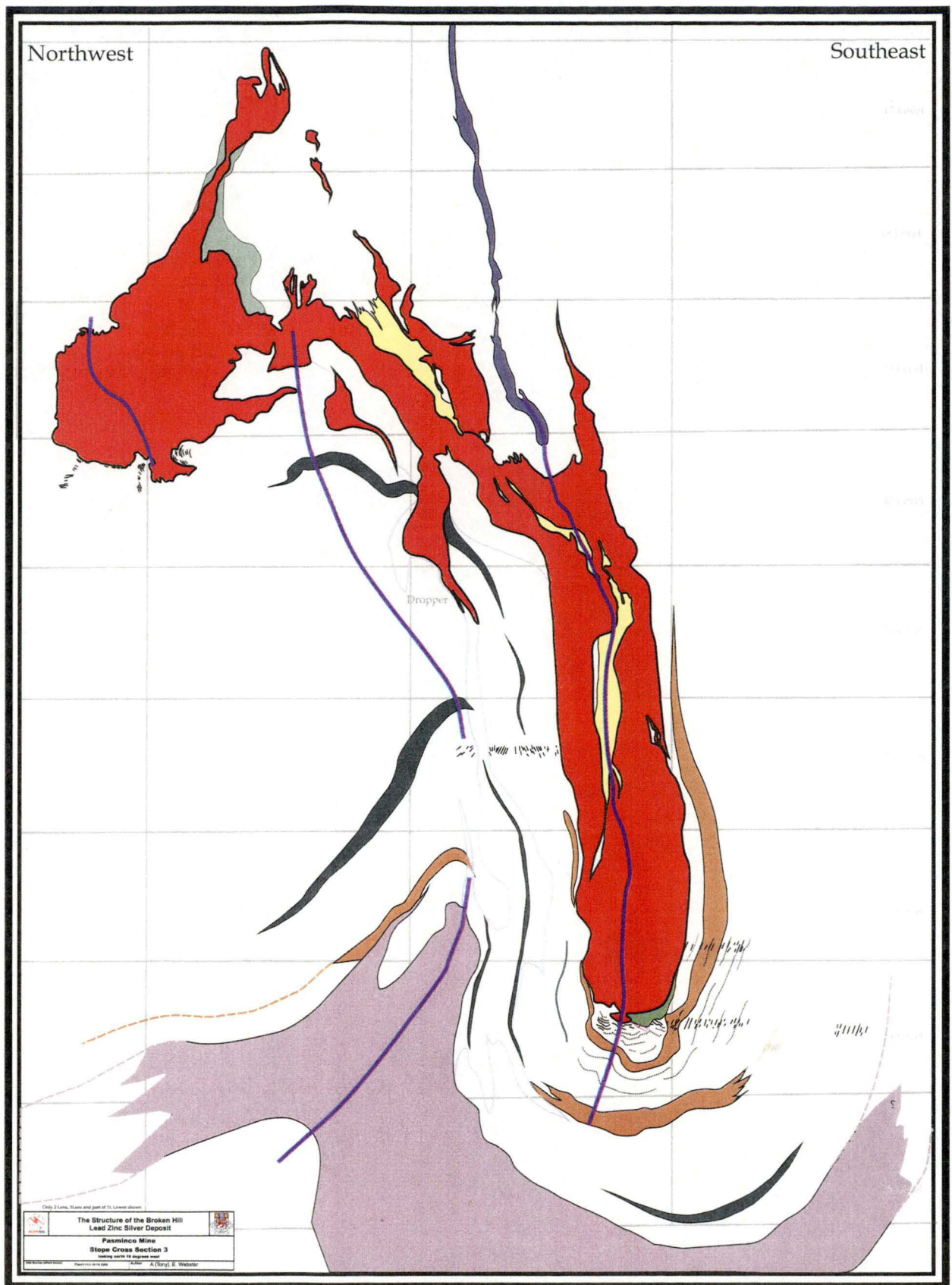


Figure 5.7. Pasmaico Mine Stope Cross Section 3 showing relationship between 2L, internal stratigraphy and the 'underwall zone' of the Footwall Succession. The "D1 slide" of Laing et al (1978) would need to occur between the footwall of 2L (red) and the uppermost potosi type gneiss (light brown) of the ABM Potosi Type Quartzofeldspathic Gneiss. There is not enough room in this region to accommodate such a major structure and no evidence for such a structure is seen in exposures of the sequence in the mine workings. Blue lines represent F2 axes. Refer to standard geological legend.

### Summary of the features of D2 (OLARIAN OROGENY)

F2 Folds	Alteration	Structural fabric
<p>Asymmetric south verging F2 folds that traverse the orebodies at c20° to their original strike</p> <p>Second order F2 folds: SXS, ZCA, NBHCS SMA, CMA, CMS, BHPS, B14A, BA, BS, NMA, WKS etc. Isoclinal style in the NE &amp; central mining field; tight folds in SW.</p> <p>Formation of the initiation points of 'droppers' (small scale F2 synformal folds)</p> <p>First order F2: HWS, IRS, MBA, RHS, 'Airport Antiform' ('Broken Hill 'Synform').</p> <p>Initiation of B Lode Shear &amp; related D3A structures?</p> <p><b>Northeast Region</b></p> <p>Intense D3A transposition in the northeastern region is closely associated with complex isoclinal folding &amp; the distinction between F2 folding &amp; D3A shearing is much less obvious than in the southwest.</p> <p>Very tight to isoclinal F2 folding with some transposition of ore lenses at margins &amp; dislocation of stratigraphic markers (e.g. 'epidosite' layers).</p> <p>Silicification of metasediments on 3L-2L margins in North Mine - intense silicification of wall rocks at orebody contacts (formation of GO rock)</p>	<p>Extensive mechanical &amp; fluid phase sulphide mobilisation in orebodies. Includes fluid phase sulphide migration into rhodonite-bustamite margins &amp; wall rocks (mostly garnet sandstone &amp; garnet quartzite).</p> <p>Wall rock silicification at orebody contacts (silica metasomatism), especially on margins of 3L in North Mine.</p> <p>Differentiation of sulphide constituents into Pb-Ag-Au-As-W(Cu) - rich fluid phase &amp; Zn-Fe-Cu - rich fluid phase</p> <p>Extensive development of siliceous, saccharoidal mineralised breccias, vein systems &amp; stockworks in Garnet Quartzite in tightly infolded F2 folds, especially within A Lode Lower in the hinge of the NBHCS &amp; ALL in the WKS. Process continues into D3A. Quartz-hedenbergite vein stockworks &amp; breccias &amp; alteration of garnet quartzite to garnet 'sandstone' on vein walls. Including extensive sulphide mobilisation and garnet recrystallisation in veins and wall rocks..</p> <p>Silicification and 'mineralisation' of metasediments, pegmatite &amp; pegmatitic segregations at most orebody contacts, especially in clastic metasediments Siliceous alteration of wall rocks most strongly developed in North Mine, especially at margins of 3L, to form low grade siliceous, blue quartz mineralisation, often mined as ore (originally wall rock metasediments in many cases). Smaller and weaker occurrences developed at orebody margins in Pasmenco Mine.</p> <p>Vein Brecciated Manganese Silicate Mineralisation (AL Lower). Pegmatitic sulphide veining &amp; coarse sphalerite veining within ore lens horizons &amp; adjacent garnet quartzite.</p> <p>Abundant vein quartz-hosted mobilised mineralisation in North Mine compared with relatively minor in the southwest region.</p>	<p>Grainsize coarsening of gangue &amp; sulphide</p> <p>Annealing crystallisation throughout orebodies</p> <p>Formation of varied styles of fibrolite bundles within pelitic rocks</p> <p>S3 axial plane foliation defined by galena distribution in 3L in North Mine</p> <p>Extreme recrystallisation of rhodonite at margins of rhodonite masses in 2L.</p>

**Figure 5.8.** Summary of the features of the first significant phase of deformation within the Broken Hill mineralised system and Mine Sequence (D2).

### 5.5.1. S2 Fabric.

A strong axial planar foliation (S2) was developed within metasediments during D2 and refolds S1 (Rutland & Etheridge, 1975; Laing, et. al., 1978). However, even where S2 was most intensely developed, such as in pelitic units, the S1 fibrolite 'bundles' are often preserved in S2 crenulations (Laing, et. al., 1975).

Where fully developed in metasediments, S2 is defined by folded and flattened aggregates of fibrolite or sillimanite and by the preferred orientations of new sillimanite and biotite. S2 is typically only developed within or adjacent to F2 fold hinges. S1 can be preserved within psammitic layers while the same fabric in adjacent pelitic bands can be completely obliterated by S2. In quartzofeldspathic gneisses, quartzofeldspathic segregation veinlets frequently developed in the axial planes of F2 folds and form a penetrative surface that may be developed away from the fold (Laing et al., 1978)

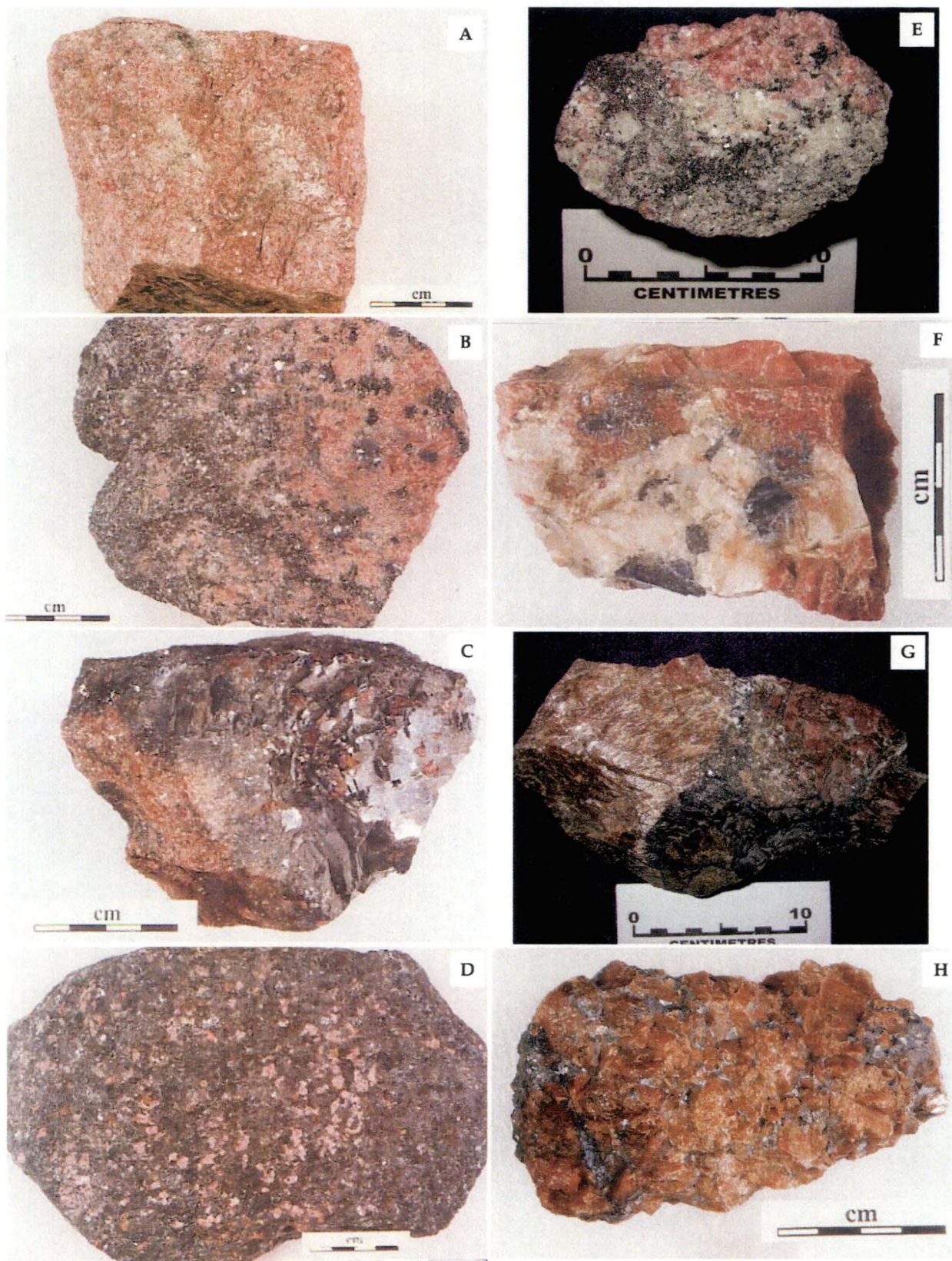
D2 is manifested in the orebodies as folds, extensive zones of sulphide mobilisation, quartz-sulphide and sulphide vein stockwork systems, widespread development of often mega-crystalline manganese and calc-silicate pyroxenes and pyroxenoids (Figure 5.9) (Webster, 1994a) and extensive siliceous metasomatism within mineralisation and wall rocks (Webster, 1994a; Prendergast, 1996). A pervasive S2 axial planar fabric defined by lead grade distribution (galena distribution) formed in 3L in the North Mine (Figure 5.10 & Figures 4.22, 4.23 & 4.24, all contained in separate map folder). A weak alignment of galena grains is observed in the banded calcitic ores of 2L in the Pasminco Mine (Figure 4.31e) but the pervasive fabric is absent to the southwest of the Junction and British Mines.

### 5.5.2. F2 Folding.

Two orders of F2 folding (in the sense of Hobbs et al., 1976) have been identified in the BH area; first order folds are of regional importance and second order folds are important at a deposit and orebody scale. Second order folds are parasitic upon first order folds.

F2 folding throughout the mining field is asymmetric and south verging, however, folds are southwest plunging in a domain to the southwest of the Block 14 Mine ("S"





**Figure 5.9.** Hand specimens of the various habits of rhodonite found within the Broken Hill orebodies (in this case, predominantly from 2 Lens in the Pasminco Mine). The selection from A (massive equigranular unmineralised rhodonite from the 20 Level, Pasminco Mine) to D (dispersed crystals of rhodonite in massive sulphide matrix from North Mine) is interpreted to represent progressively more recrystallised and mobilised-sulphide mineralised styles formed during D2. Specimen E shows rhodonite in its bright pink form within banded calcite ore in 2L. Specimens F and G show the coarsely recrystallised forms of rhodonite found on the deformed margins of equigranular rhodonite masses in 2L and H shows the coarsely crystalline bustamite commonly found in 2L in the ZC area of the Pasminco Mine, within D2-D3A attenuated masses of calcitic ore.



folds); reversing to northeast of the British Mine ("Z" folds) (Figure 5.11 & 5.12). The vergence of the second order F2 throughout the field is consistent with a location on the northern limb of a regional first order F2 antiform lying to the southeast of the mining field. The style of folding within the orebodies is similar to that described by Lewis et al., (1965).

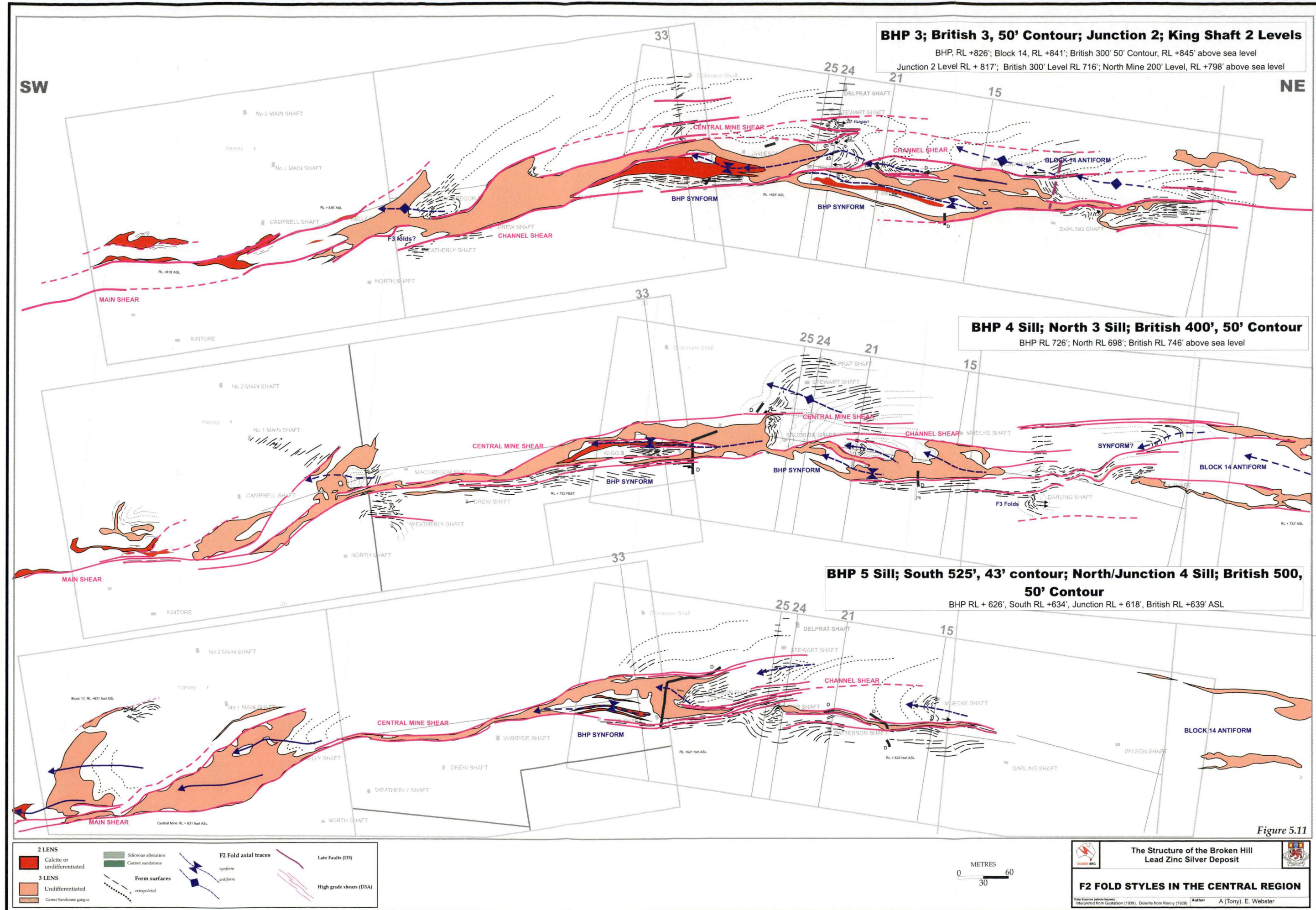
F2 folds plunge towards the southwest in a domain extending from the southwestern end of the Block 14 Mine ( $< 10^{\circ}$  to  $35^{\circ}$ ) and plunge northeast from a position approximating the southwestern end of the British Mine (in the vicinity of the Blackwoods Shaft/open cut). Throughout most of the Block 14 and BHP mines F2 fold plunges undulate around the horizontal; a position that marks the plunge reversal in the centre of the mining field (Figures 5.12 & 4.14).

#### 5.5.2.1. *First order F2 folds in the mines area.*

Two macroscopic first order F2 folds dominate the BH area and are known as the Hangingwall Synform (HWS) and the "Broken Hill Synform" (BHS) (e.g. Andrews 1922; Laing et al., 1978) (Figure 5.13, in separate map folder). Two further first order structures are also important in the northern leases and are known as the Martins Bore Antiform and the Imperial Ridge Synform. The folding that is observed within the orebodies and throughout the mining field is parasitic on the HWS and 'BHS' and of the same generation. The deposit lies within the common steep northerly dipping limb of the two folds. The most important folds of this type are discussed below.

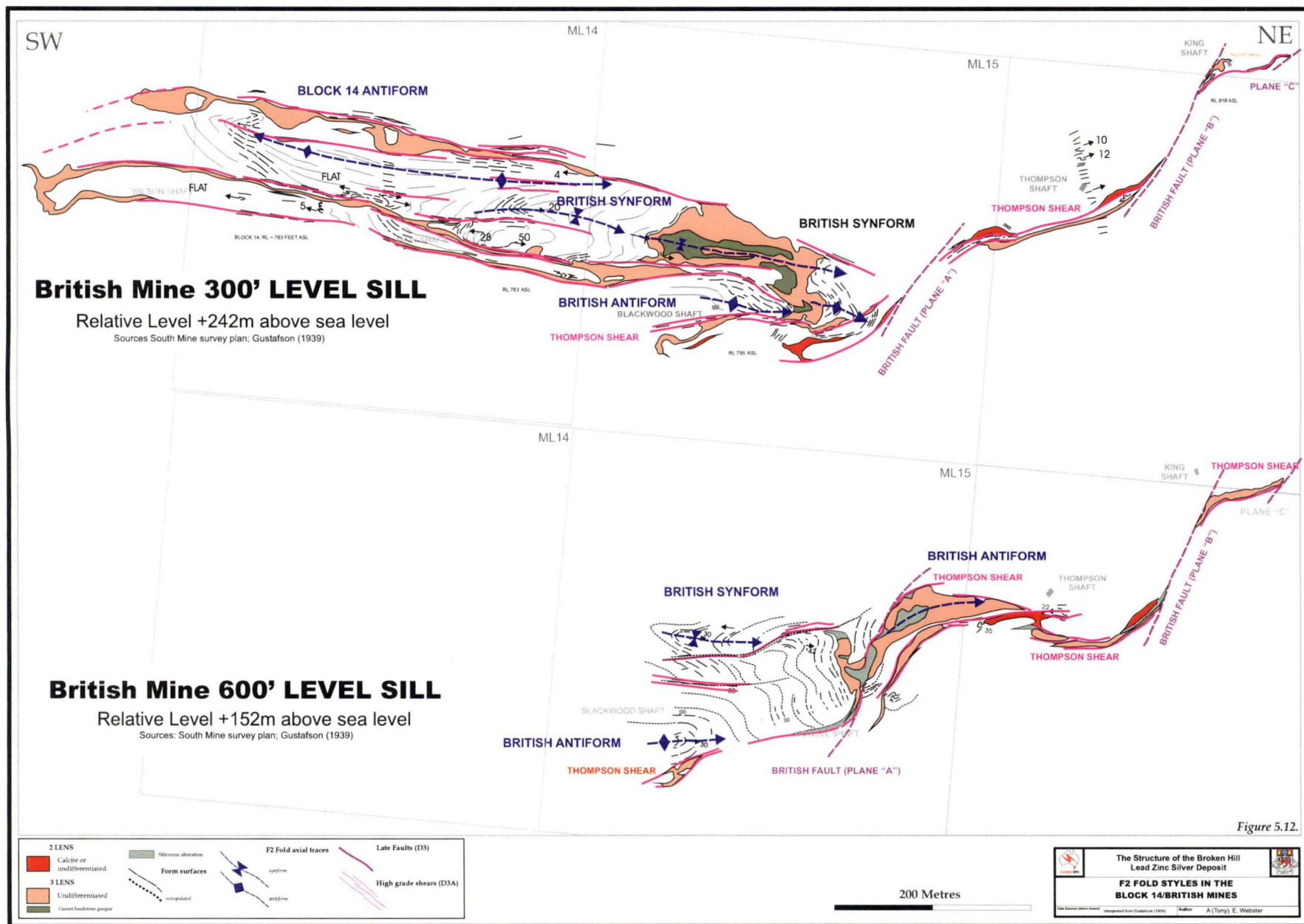
**The Hangingwall Synform.** The Hangingwall Synform (HWS) lies within the centre of the City of Broken Hill, parallel to the mining field, and extends to the northeast and southwest of the urban area (Figures 4.1, 5.1 and 5.13). It has an outcropping strike length of 13 kilometres.

The HWS has been interpreted in the past to be a simple 'boat' shaped structure (e.g. Schuler et al, 1993) with the Hangingwall Quartzofeldspathic Gneiss (HWQG) at its core and a fold axial trace that follows the long axis of the lensoidal outcrop geometry. However, the distribution of an apparent mineralogical zonation within the HWQG (Figure 4.1) and the folding of the well-defined S1 segregation banding (e.g. Ransom, 1969; Vassallo & Vernon, 2000) show that the HWS has a great deal more asymmetry and geometric complexity than previously suggested (Figure 5.13).



**Figure 5.11.** Level plans showing the F2 fold styles in the orebodies in the central region of the mining field. Interpreted from Gustafson (1939). Information about dolerite occurrences is from from Kenny (1929); BHP 3; British 3, 50' Contour; Junction 2; King Shaft 2 Levels BHP 4 Sill; North 3 Sill; British 400', 50' Contour BHP 5 Sill; South 525', 43' contour; North/Junction 4 Sill; British 500, 50' Contour.





**Figure 5.12.** Level plans showing the F2 fold styles in 3 Lens in the Block 14 and British Mines of the central region of the mining field. Interpreted from original data of Gustafson (1939). British Mine 300 Level Sill and British Mine 600 Level Sill.

Large masses of the HWQG are tightly to isoclinally folded and appear to have some dislocation along common limbs, at least on the northeastern end of the main mass, in the Block 10 Hill area. The HWS probably comprises a series of asymmetric southerly plunging parasitic fold structures that are dislocated on common limbs by early retrograde shears.

Plunge varies from 35° SW to 45° NE (Laing et al., 1978) and defines the same plunge culmination that is seen in the orebodies in the Block 14 mine area.

**The Martins Bore Antiform.** There are no formal references to the definition and nature of the Martins Bore Antiform (MBA). However, it is a fold structure that is well-defined in surface mapping of all eras of investigation at BH, being depicted on many surface geological maps of the north-eastern part of the mining field (e.g. Andrews, 1922; Gustafson, 1939, Henderson, 1956; see Figures 4.1, 5.1 and 5.13). The structure is also one that was generally recognised in day-to-day exploration in the North mine and Pasminco mine geology departments until final mine closure in 1993. It appears to have originally lain to the southeast of the Hangingwall Synform prior to dislocation by the DeBavay Shear and British Fault system (Figure 5.14, contained in separate map folder). It lies to the northwest of the Imperial Ridge Synform and is truncated to the northeast by the Globe-Vauxhall Shear Zone (see below).

The MBA lies to the immediate southwest of the D3B DeBavay Shear zone within a shear-bounded domain preserved between the Globe-Vauxhall Shear Zone to the north and the DeBavay Shear zone to the south and southeast. The entire Hangingwall Succession of the MinSeq is preserved in the hinge of the fold, including the Upper Potosi Type Quartzofeldspathic Gneiss, elements of the Town Amphibolites and the blue quartz lode rocks of the Lode Sequence. A remnant of the hinge of the MBA is also defined by the Hangingwall Quartzofeldspathic Gneiss within the DeBavay and Globe-Vauxhall Shear zones to the northwest of Imperial Ridge though it is significantly reduced in thickness compared to the main development southwest of the DeBavay Shear Zone (Figure 4.1).

**The Imperial Ridge Synform.** To the east-southeast of the Hangingwall Synform and Martins Bore Antiform is another F2 structure known as the Imperial Ridge Synform (IRS; the Imperial Ridge Syncline of Henderson, 1956) (Figure 5.13, in separate map

folder). The fold is mainly defined by a large ovoid mass of amphibolite in the core and a narrow belt of HWQG and Lode Horizon within the southwestern hinge. Lode Horizon persists throughout much of its southern limb.

The IRS lies within a zone northeast of the British Fault, to Imperial Ridge in which F2 folds plunge at varying angles. At Imperial Ridge, F2 folds are sub-horizontal and further to the northeast, at Round Hill they revert to the regional southwest plunge (Laing et al., 1978). The vergence of the folds is predominantly 'S' vergent until the plunge reversal near Round Hill returns the fold plunge to the more general southwestern direction (Laing et al., 1978) and an opposite 'Z' vergent form occurs.

**The Broken Hill 'Synform'.** The Broken Hill 'Synform' (Andrews, 1922; Laing et al, 1978) is perhaps the most obvious outcropping fold structure in the BH area (Figure 5.13). It lies to the south and southwest of the mining area, centred around the Broken Hill airport but with a surface trace extending northeast and southwest of the city; a total outcropping strike length of over 25 kilometres. The BHS has the same northeast-southwest trend as the HWS and other first order F2 structures north and northeast of the mines area. The core of the BHS is occupied by the Alma Augen Gneiss (Figure 4.1).

The geometry of the stratigraphic units defining the outcrop pattern of the Broken Hill Synform strongly suggests that it is an antiform if it plunges to the northeast at the northern end of the mining field and southwest at the southern end, as do all other major structural elements of this area. It is therefore suggested that the Broken Hill Synform has been incorrectly interpreted by previous workers and is actually a refolded antiform (Webster, 1996b). If the Broken Hill 'Synform' is an antiform, then it possesses a common limb with the Hangingwall Synform that contains the Broken Hill orebodies and may represent the F2 antiform to the south of the mining field that is suggested by the second order fold vergence seen in the orebodies (see below).

The results of a recent seismic reflection survey carried out along a transect crossing the HWS, mining field and the BHS was interpreted as being more compatible with an antiform, rather than a synform in the position of the Broken Hill 'Synform' (AGSO, 1997). As was discussed at length in Chapter 4, the stratigraphic succession of the MinSeq in the mines area is more compatible with an upward, north facing sequence in the mines area and is not structurally repeated by a "Broken Hill Antiform" as was

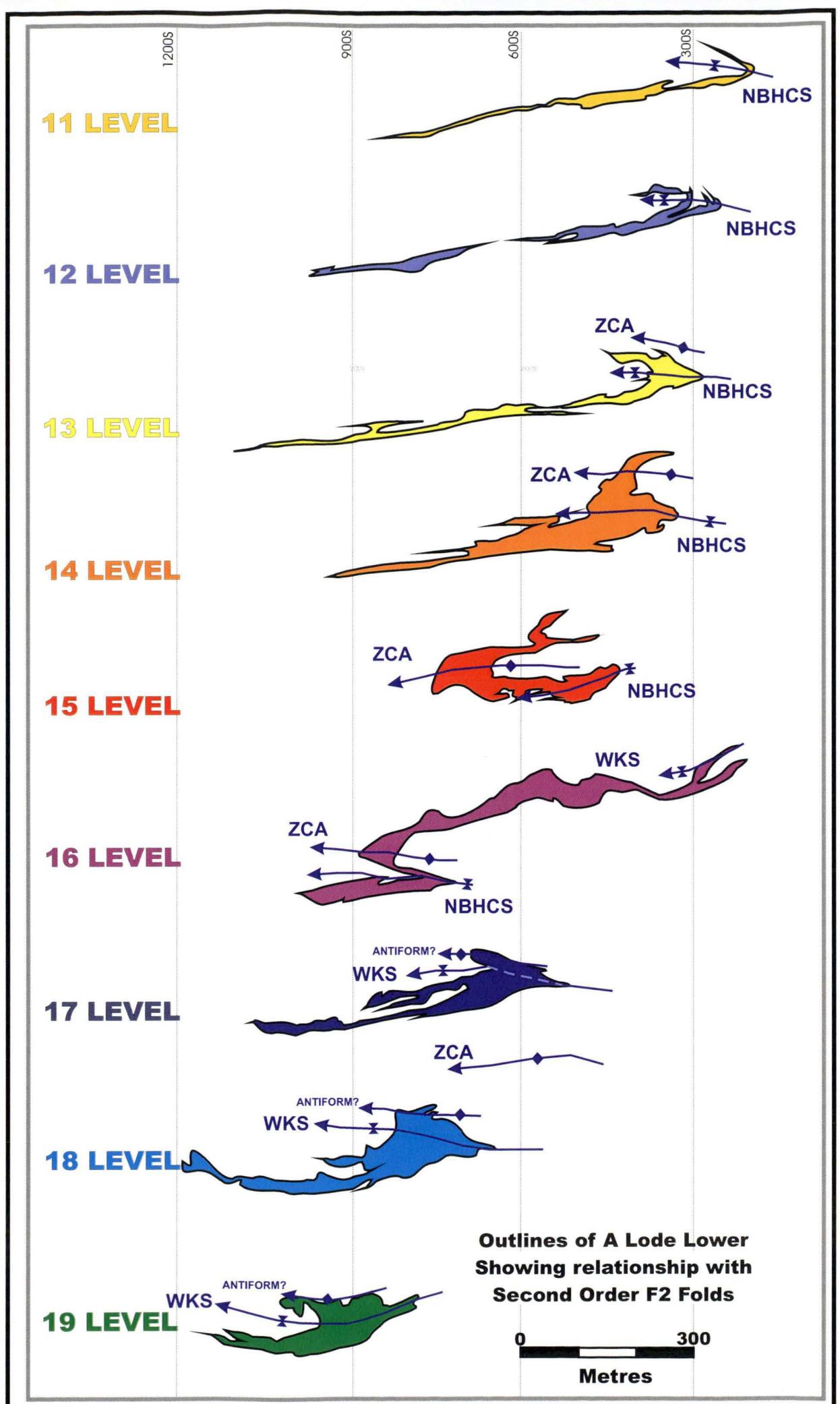


Figure 5.15. Outlines of A Lode Lower showing the relationship between the orebody and the main second order F2 Folds in the Pasmaingo Mine (The ZC Antiform and the NBHC Synform). The linear trend of the orebody is transected by the southwest plunging folds shown as blue lines).

invoked by Laing et al (1978) to occupy the position between the HWS and the BHS. If the BHS is in fact antiformal, it negates the requirement for a "Broken Hill Antiform".

The precise nature of the structure named the Hangingwall Synform is unclear. The internal zonation of the Hangingwall Quartzofeldspathic Gneiss defined by GSNSW mapping, and the folded traces of the foliation trends (S1?) within it suggest that it is a more complex, asymmetric and convoluted structure than the relatively simple boat shaped keel interpreted by previous workers (e.g. Gustafson, 1939; Laing et al., 1978). While it has not been possible during this study to investigate this structure in detail, it has been identified as a key element of the MinSeq stratigraphy whose geometry, internal zoning, structure and place in the sequence requires further detailed analysis.

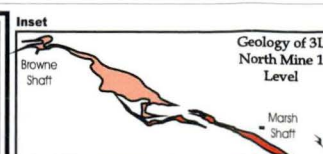
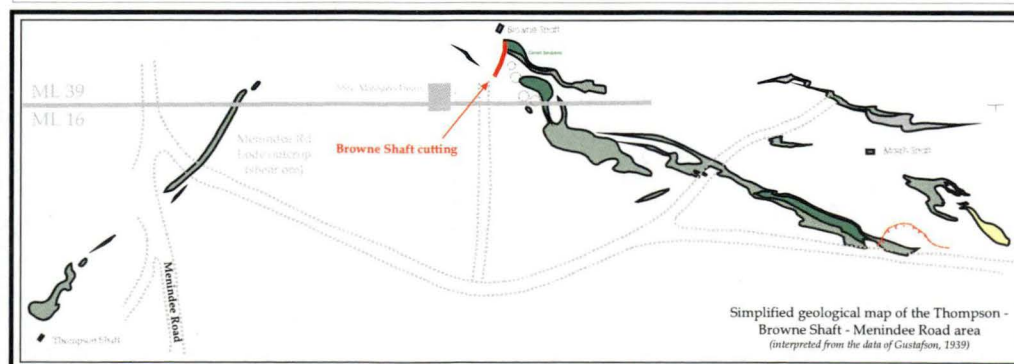
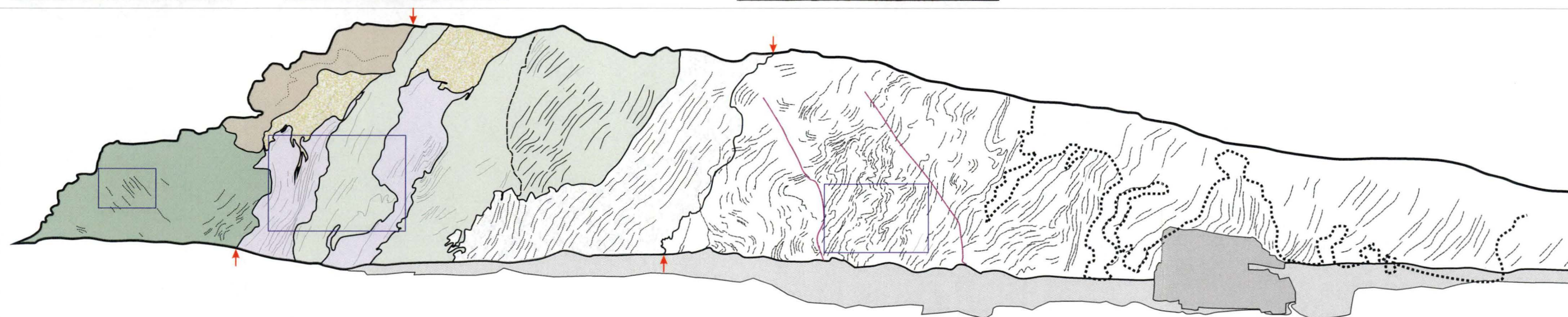
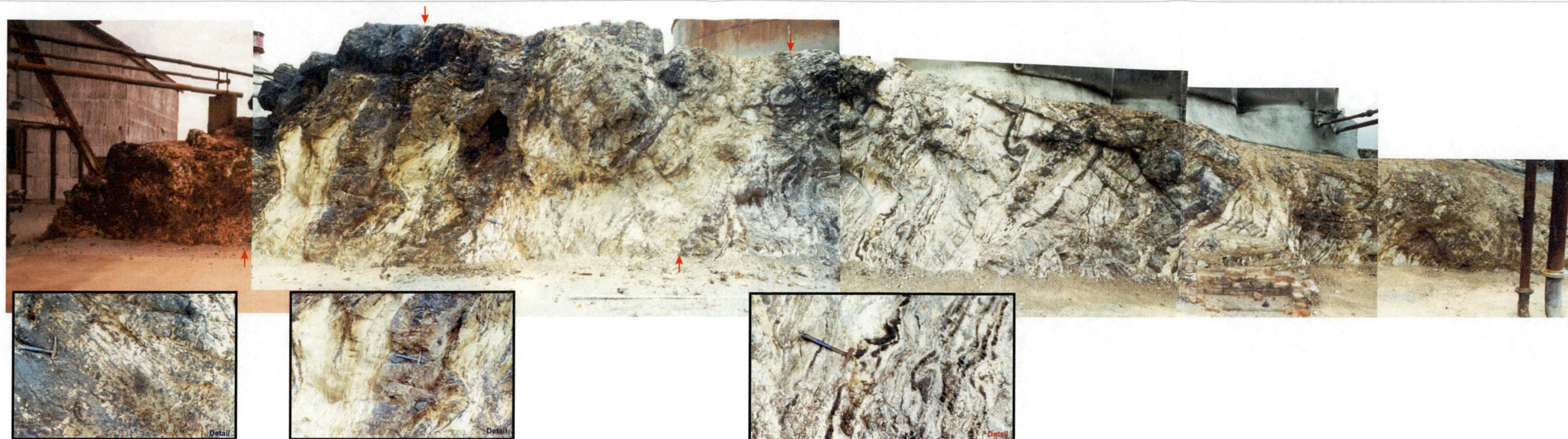
Both the Hangingwall Synform and the BH Synform of Laing et al (1978) are now seen to be more complex and less well understood than previously supposed. The interpretation of these structures as relatively simple, regional F2 synforms is the main reason for the interpretation of an F2 BH Antiform within the MinSeq by Laing et al., (1978). The BHA in turn is interpreted to be the cause of the repeat of the MinSeq stratigraphy by these authors. If the HWS is more complex than previously supposed, and the BHS is potentially an antiform, or at least more complex than previously interpreted, then the nature of the BHS and HWS needs to be more fully investigated and defined before the 'problem' of the BHA can be fully laid to rest.

#### 5.5.2.2. *Second order F2 folds.*

Within the Lode Sequence, parasitic second order F2 folds are the most important structures at mine scale and have had profound effects on the geometry of 2L and 3L (e.g. Figures 4.19, 5.10, 5.11 & 5.12). Throughout most of the mining field, second order F2 folds form an en-echelon set (Lewis et al, 1965) of northeast-southwest to east-west trending, south verging and gently to steeply southwest plunging, mesoscopic and macroscopic folds with south-east dipping axial surfaces. From a point near the Blackwoods Shaft/open cut, to depth in the North Mine, second order F2 folds plunge shallowly to steeply northeast.

Second order F2 folds transect the trend of the orebodies at approximately 15 to 30 degrees to their strike (Figure 5.15), are strongly asymmetric, with longer northwestern limbs on antiforms. Second order F2 folds are tight to isoclinal in style and most





- Coronadite impregnated shear
- Coronadite cap
- Base of coronadite impregnation
- Quartz-sericite shear
- Retrogressed metasediments
- Garnet sandstone (some coronadite)
- Weakly mineralised metasediments (lode rocks) (strongly altered to coronadite)
- Bedded psammopelinite/pelite variably kaolinised and feruginised

**Figure 5.16.** The prominent outcrop at the Browne Shaft brace forms a small razorback surmounted by strongly folded 3 Lens ore (now gossan). The garnet sandstone zone on the footwall of 3 Lens outcrops on the northern side of the face of the cutting and comprises weathered, friable, strongly banded garnet sandstone with manganese oxide bands. This exposure reveals the same geology of the 3 Lens footwall that is seen in successive underground levels of the Junction, Junction North and North Mines below the outcrop. This outcrop is the only place on the mining field where the geology of one of the major orebodies can be observed at surface in detail and which is a true reflection of the geology of the orebody at depth in the underground workings.

**Figure 5.16**  
**Outcrop of 3 Lens and its footwall rocks. Browne Shaft lookout cutting. Face sketch (compiled from photo montage and measured face sketches).**

Compare structure in outcrop with the structures on 27 Level North Mine detailed interpretation



intense in the central and northern areas of the deposit where they are convoluted and associated with significant transposition in the adjacent wall rocks (Figures 5.10a to c).

Isoclinal folding in the northeastern area (chiefly within North Mine) is associated with transposition and shearing along fold limbs, ore-metasediment contacts and extensive siliceous metasomatism in wall rocks. The northeast area is the only part of the mining field where a strong axial plan foliation (S2) is developed in the orebodies. Lead grade mapping reveals this fabric to be mimicked by galena distribution (see below). The intensity of F2 folding in the northeastern part of the deposit is also reflected in the metasediments where intense crenulation of coarse D1 fibrolite bundles by S2 within pelitic units affected by F2 folding is common (Figure 5.16), a feature that is not seen in the southern half of the deposit to the same degree.

The style of F2 folding remains consistently open to tight in style throughout the Pasminco and South Mine areas but becomes very tight to isoclinal near Delprats Shaft on the BHP Mine, where extensive syn-D2 to D3A transposition of wall rocks and mineralisation was associated with folding (Figure 5.11).

The asymmetry of second order F2 folds within the orebodies is consistent with their being parasitic on the northwestern limb of a south plunging antiform with an axis lying to the southwest. The recent suggestion that the first order BHS is actually an antiform (Webster, 1996b) would add weight to this interpretation and is supported by the vergence of second order folds.

Second order F2 folds diminish in intensity at the southwestern end of the mining field as the orebodies plunge out of the common limb area of the HWS and 'Airport Antiform' (Broken Hill 'Synform') and into the less intensely folded region of the shoulder of the HWS. Therefore, in the Southern Cross Shaft and southern leases area of the Pasminco mine, the stratigraphy is mostly planar, with only minor F2 buckling.

Previous workers have invoked a model of folding in the orebodies in which a single persistent fold pair predominates throughout the length of the mining field; the "Western Antiform" and the "Eastern Synform" (e.g. Gustafson, 1939, but most recently Laing et al, 1978). Interpretation of the geometry of the folds throughout the orebody from surface, through successive mine levels to depth has allowed a detailed picture of the geometry of second order folds in the orebodies, LH and in the

surrounding MinSeq stratigraphy to be defined and the changing geometry of these structures to be 'followed' down plunge through the mines. This work has produced a view of the folding that is more akin to that of Lewis et al., (1965) whereby a series of separate fold structures are identified throughout the mining field. Therefore, the use of the terms "Western Antiform" and "Eastern Synform" (Laing et al, 1978) and their earlier equivalent-named structures known as the Western Anticline and Eastern Syncline (e.g. Gustafson, 1939; King and Thomson, 1953) is abandoned for the purposes of this study, despite their long standing use on the field. The names are abandoned altogether because of the confusion that may arise with their continued use in this scheme. These terms are still in use on the Pasminco Mine at the southern end of the field where they will be referred to as the ZC Antiform, NBHC Synform, Southern Cross Antiform and Southern Cross Synform.

The interlimb angle of individual orebody-scale folds is difficult to determine because there has been significant (often extreme) modifications of the limbs by post-fold shearing and attenuation. However, examples of less modified folds are seen in the Block 14, South and Pasminco mines within 2L and 3L. The original F2 fold style was relatively open to tight with angular hinges in this region, as is still well-preserved by the Block 14 Antiform (see below).

Laing et al., (1978) interpreted the second order folds in the orebodies to be retrograde F3 structures imposed upon the macroscopic first order F2 folds. However, Webster (1993, 1994a) discounted this interpretation based on the recognition of high metamorphic grade fabrics developed in the orebodies during second order fold development and because of the overprinting of second order fold geometries by strongly developed high grade D3 shear zones and associated S3 fabrics that are equated with the D3 of Laing et al (1978) (see below).

Rather than describe each individual fold structure, the nature of several key examples will be discussed in detail. For locations of all structures on each mine level, refer to the level plans included in Appendix 1 (at the rear of this thesis) where the trace of all recognised fold structures is marked on separate overlay layers).

The most important second order F2 folds are described in the following sections (by region – refer to Figure 1.1). The fold nomenclature used for the Central Region was

presented in a preliminary form by Webster (2000a) and has been subsequently modified.

#### 5.5.2.3. *Second order F2 folds in the Central Region.*

**The BHP Synform.** The geometry of 3L is variable through ML 11 to 13; having a shape that is produced by the interplay of its early ribbon-like form, a complex tight to isoclinal synform (the BHP Synform) and the effects of high grade sinistral shears that have extensively dissected, attenuated and dislocated the fold (Figures 5.11 & 5.12). The BHP Synform (BHPS) is a nearly isoclinal structure but is convoluted, comprising a series of smaller folds hinges. The fold is best-defined where the orebodies lie within it and this has been the site of intense post D2 shear-modification.

The BHPS has a variable, but shallow to moderate undulating plunge throughout the BHP Mine. The BHPS has a shallow southwesterly plunge in the southwestern part of ML 11. The plunge reverses midway through ML 11 before returning to a shallow southwestern plunge again near the boundary of ML 12. From ML 12 to the northeastern end of ML 13, the folds are shallow southwest to horizontal in plunge. It is the zone of undulating plunge in ML 12 that formed the central arch of the deposit and which brought the mineralised rocks closest to the palaeosurface, within reach of the weathering processes. A narrow 'sheet' of sheared sulphides and lode rocks projected upwards from the sheared limb area and it is mainly this material that outcropped in ML 12, producing the prominent coronadite outcrop that was exposed at the time of discovery.

The hinge of the BHPS is dislocated by D3A shearing and now occurs as two almost separate segments that are dissected by the Channel Shear (Figure 5.11, see section 5.5.2.1). 3L lies within the hinge region of the fold for much of ML 11, 12 and 13, progressively migrating across the remnants of the hinge area from southwest to northeast. For much of former ML 12 and 13 the orebody lies in the complex synform hinge (Figure 5.17). The orebody is drawn out and structurally thinned in the fold limbs where D3A shearing is most strongly focussed. 3L is therefore a tightly convoluted orebody in this area, consisting of elongate pipe-like masses of sulphides and silicate-carbonate gangue (preserved fold hinges) linked by thin 'sheets' of sheared sulphide rocks (attenuated fold limbs).

2L mineralisation is restricted to a thin, dismembered segment preserved within the keel of the synform and formed a vertical to steeply dipping shoot within the fold keel (Figure 5.11 & 5.17). The shoot outcropped as the “Eastern Lode” identified by Jaquet (1894).

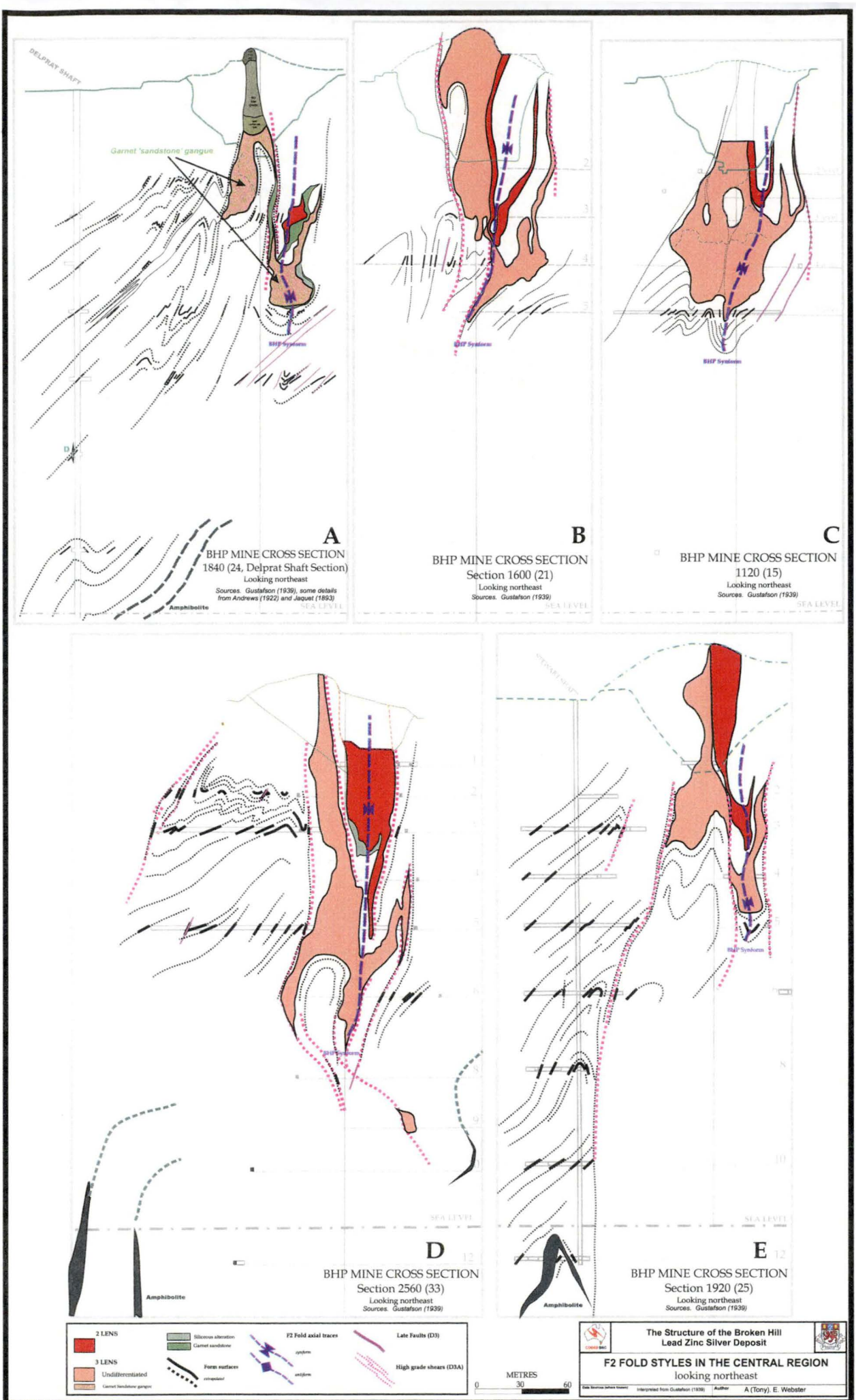
The BHPS hinge is lost due to attenuation and fold and shear complications near Rasp’s and Wilson’s Shafts and it is this point where the orebody is at its thinnest (Figure 5.11, see maps BHP1, BHP2 and BHP3C in Appendix 1). To the southwest, in the Central Mine area the Central Mine Antiform comes into prominence (see below). To the northeast, the Block 14 Antiform predominates.

**Block 14 Antiform.** The geometry of 3L is simple in ML 14, lacking the convolutions and intense shearing of the BHPS to the southwest. The orebody geometry is mainly controlled by a single broad, tight antiform; the Block 14 Antiform (B14A), which comes into prominence to the northeast of Rasp’s Shaft on ML 13 and which persists into ML 15. The B14A forms the complimentary antiform to the BHPS on the northeastern side (Figure 5.18).

The axis of the B14A is generally horizontal but undulate in plunge from shallow southwest to shallow northeast. From near the boundary with ML 15, the plunge becomes progressively steeper to the northeast to the point where the orebody is truncated at depth by the Thompson Shear (see later).

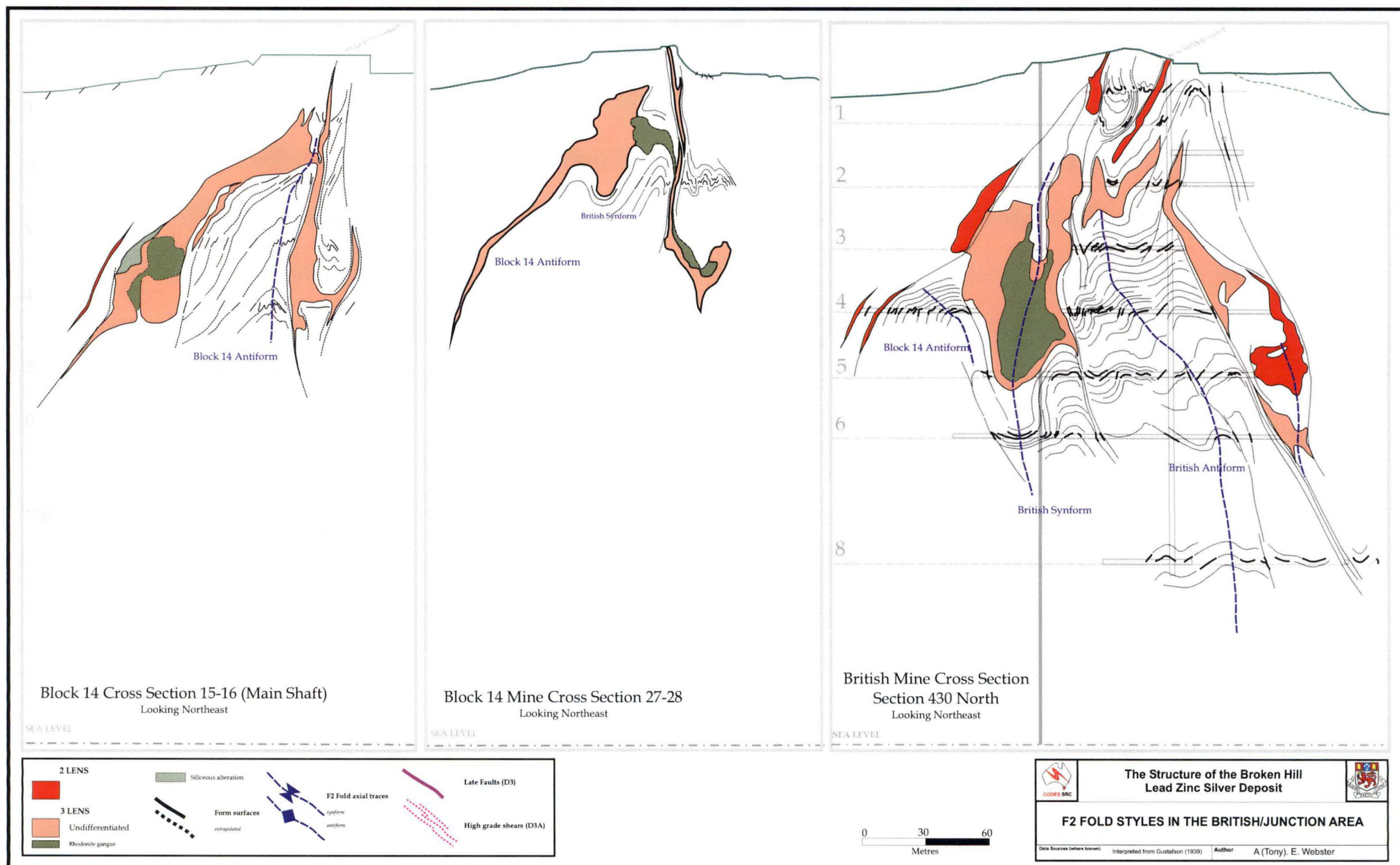
3L is mostly focussed in the northwestern limb of the B14A in the southwest of ML 14 but gradually migrates across the fold hinge to the northeast, crossing the hinge in the region of the ML 14-15 boundary. 3L is thus “draped” across the hinge of the antiform, while defining both the southern and northern limbs of the fold (Figures 5.18 & 5.12). Near Blackwood’s Shaft, the main mass of 3L enters the hinge of the British Synform (Figure 5.12), just southwest of the position where the D3A Thompson Shear truncates it (see below). 2L mineralisation is only preserved on the 1 Level of the British Mine within the keel of the British Synform (see below) and is sheared out at depth by the Thompson Shear on the northeastern boundary of the mine.

Shearing is present within the common limb of the B14A and British Synform throughout ML 14 and 15, with an apparent west block up movement. Shear hosted



**Figure 5.17.** Cross sections showing the F2 fold styles within the orebodies in the central region of the Broken Hill mining field (BHP Mine). Looking northeast. Compiled from the data of Gustafson (1939). Amphibolites are shown in dark green. The F2 folds in this region of the deposit are strongly affected by D3A shearing. The orebody geometry is dominated by the BHP Synform. Section locations shown on Figure 5.10.





**Figure 5.18.** Cross sections of the British-Junction Region of the Broken Hill mining field (Block 14 and British Mines) showing the F2 fold styles in 3 Lens and 2 Lens. Looking northeast. Compiled from data collected by [Gustafson \(1939\)](#).



mineralisation, projecting upwards from the hinge mineralisation, forms the linear lode outcrop throughout ML 14 and 15 (Figure 5.1, in separate map folder).

**The British Synform & British Antiform.** A complimentary tight to isoclinal synform lies to the south of and parallel to the B14A, coming into prominence just to the southeast of the Blackwoods open cut. The fold is named the British Synform (BS) and is best defined by a thick mass of 3L ore that contains a well-defined rhodonite layer (Figure 5.12, 5.18 & 4.26). 3L ore within this fold provided most of the ore mined from the recent remnant open cutting operation. The fold was described as a “tear drop syncline” by Garretty (1943) in reference to the pinched off ore extensions to the fold that were identified below the main keel.

The axis of the BS is approximately horizontal in ML 14 but undulates in plunge from shallow southwest to shallow northeast. From near the boundary with ML 15, the plunge steepens sharply and the 3L ore within the synform keel defines a thickened mass in a keel that plunges northeast at 60° to 70°. The hinge mass is bounded on either side by D3A shearing (see below) and seems to comprise a relatively isolated mass preserving F2 geometries between two D3A shears. The fold diminishes in intensity with depth to the northeast and is truncated at depth by the Thompson Shear (see later).

To the southeast of the BS, an antiform of similar complex style is developed, mainly within the metasediments adjacent to 3L. The structure is only poorly defined because of the intense D3A shearing that has dissected it. It is named the British Antiform (BA) (Figures 5.18 & 5.12). D3A shearing focussed along 3L within the common limb of the BS and BA dislocates a mass of 3L ore within the hinge of the BA to the northeast. A significant remnant of the structure is preserved as an isolated pod (or ‘shoot’) of ore that is best developed between the 3 and 10 Levels of the British Mine, between Blackwoods and Thompson Shafts (Figure 5.12, Figure 4.14 & 4.26).

**Folds in the Western Mineralisation.** The en echelon arrangement of second order F2 folds within the main orebodies is also seen in the Western Mineralisation (WMIN) further to the north of the main mining area (at depth beneath the urban area). The WMIN folds are less strongly developed than in the main orebodies and are defined by the geometry of the main sulphide occurrences associated garnet quartzite and particularly the geometry of the B Lode Horizon rocks that host the zone.

F2 folds are strongly asymmetric and seem to be relatively open, southwest plunging, south verging structures that may be dissected by high grade shearing (refer to maps NBH6 and STH1480, in Appendix 1).

#### 5.5.2.4. *British-Junction Region.*

In this region of the mining field, the main orebodies are severely attenuated and F2 folds have been attenuated and transposed within the D3A Thompson Shear. F2 Fold geometries are virtually destroyed and 3L has been 'drawn out' into a thin ribbon of mineralisation with occasional larger masses and 'swellings' of sulphides and lode rocks representing remnants of preserved F2 fold hinges. Movement on the Thompson Shear has offset the North Mine area from the remainder of the deposit in a sinistral, southwest block up sense. The strong swing in the strike of the outcrop reflects the strike of the Thompson Shear and to a lesser extent, the British Fault (see below).

Throughout ML 16, between Thompson Shaft and Browne Shaft, there are outcropping thin, poorly developed and sinuous outcrops of garnet quartzite, gossanous coronadite-rich rocks and garnet sandstone that reflect sheared and structurally thinned lenses and slivers of sulphides and lode rocks at depth within the Thompson Shear (see below). All of these outcrops, including the sinuous, tabular and lenticular bodies of lode rocks and segments of 3L are associated with larger, shear and fault-dislocated bodies that lie within the Thompson Shear. Shear bounded sulphides lenses occasionally reach orebody proportions at depth, such as the "King Shaft Orebody". The most significant masses of and swellings of sulphides within the Thompson Shear possibly represent pre-shearing F2 fold hinges that have retained some degree of their original geometry. The Thompson Shear is described further below.

At depth in the British Mine and in the upper levels of the North and Junction Mines, the folds within 3L have been attenuated and transposed within the plane of the D3A shear and most of the folded geometry has been destroyed. The orebody is essentially a lenticular sheet. Additional complexities of orebody geometry and disposition in this area are caused by the multiple planes of the D4 British Fault, which dislocate the D3 fabric and associated localised F4 folding (see below). D4 faults offset the North Mine area up, in a reverse sense, relative to the central and southwestern parts of the mining field (Figure 4.14). This event is discussed further below.

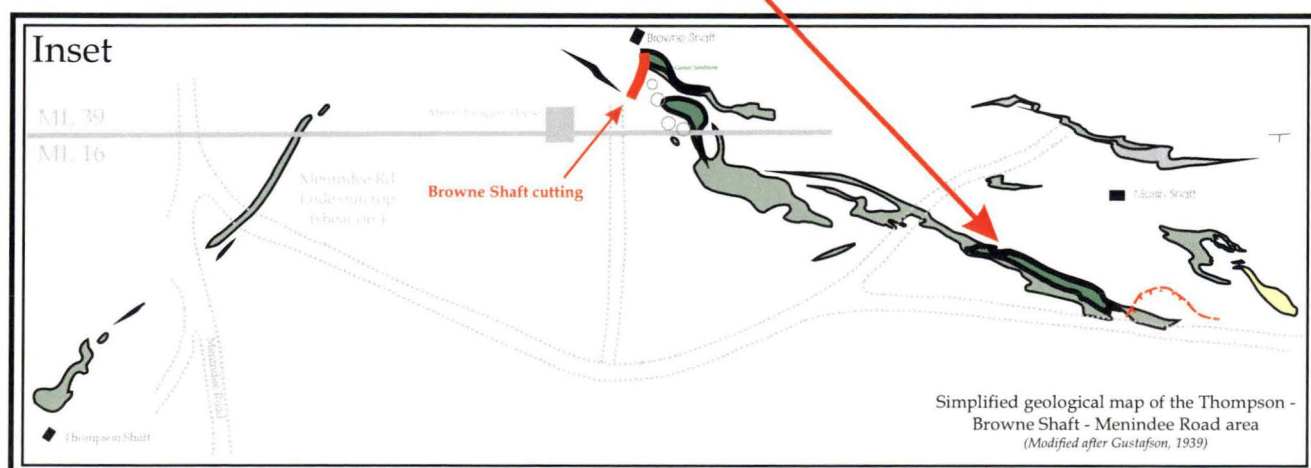
#### 5.5.2.5. *Second order F2 folds in the Northeastern Region*

The North Mine lies northeast of the Thompson Shear (ML 16 and 39) and for the purposes of this study is also taken to include the Browne Shaft area of the former Junction Mine. Mineralisation is dominated by 3L though 2L is significant. The apparent reversed dip slip movement of the Thompson Shear resulted in 3L and 2L being uplifted in the Browne Shaft-North Mine area, relative to the southwestern block and therefore brought closer to the surface than they were in the Block 14 and British Mine areas (Figure 4.14). The result is that similar fold geometries are seen in the outcropping rocks at Browne Shaft, and in the upper levels of North Mine, as are seen in the shear-bounded fold structures that affect 3L and 2L at depth in the British Mine (e.g. Figures 5.12, 5.16 5.19 and 4.26. See also maps NTH1 to NTH10 and BRIT10 to BRIT1300 in Appendix 1).

Surface mapping shows that distinct and recognisable outcrops of folded 3L, dominated by garnetiferous lode rocks occurred immediately to the northeast of the Browne Shaft collar (Gustafson, 1939; Figure 5.19). The orebody geometry that is observed in outcrop and in the upper levels of the North Mine is controlled by transposed isoclinal folds that represent the direct continuation of those in ML 15 southwest of the Thompson Shear (compare F2 fold geometries in the upper North Mine; Figure 5.16 with those in the lower British Mine; Figure 5.12).

The prominent outcrop at Browne Shaft forms a small razorback surmounted by strongly folded 3L ore (now gossan). There is a strong development of 'garnet sandstone' in the lower southwestern corner of this outcrop on the footwall of 3L (weathered, friable, strongly banded garnet sandstone with manganese oxide bands). Kaolinised metasediments in the footwall of 3L are exposed in the cutting face.

This exposure reveals the same geology of the 3L footwall that is seen in successive underground levels of the Junction, Junction North and North Mines below this outcrop. It represents the surface expression of a zone that persists in the same position for over 100 metres below surface where it is recorded in mine mapping. A smaller lode outcrop immediately northeast of the Marsh Shaft sill is interpreted to be 2L. The geometry of 3L and 2L at surface is the same as that observed on the upper levels of the North Mine from the 1 Level to the 6 Level. The transposed isoclinal fold geometry preserved in the outcrops and to depth in the upper levels of the North Mine



**Figure 5.19.** Photo of outcropping garnet quartzite/garnet sandstone boudins (rounded prominent outcrops in foreground) to the northeast of the Browne Shaft cutting outcrop shown in Figure 5.16 . View is to southwest. The Browne Shaft headframe is to the right-rear of the view and the prominent ridge adjacent to the shaft is the 3L outcrop.

**Inset.** Simplified geological map of the Thompson-Browne Shaft area (based on mapping by Gustafson, 1939). The geometry of the outcropping lode rocks reflects the geometry of the orebodies at depth within the Browne Shaft workings (refer to maps NTH 2-6 in Appendix 1).

is analogous to the structures seen in the lower levels of the British Mine to the southwest of the Thompson Shear. The outcropping folds are interpreted to be the direct continuation of the geology southwest of the Thompson Shear and represent its reappearance on the hangingwall side of the structure.

Isoclinal folds dominate the shape of 2L and 3L northeast of the Thompson Shear. However, the fold geometries in the Junction Mine and in the upper levels of the North Mine are suppressed and the orebodies have a strongly lenticular shape that has been described as a flat sheet by workers such as Hobbs (1966) (see maps NTH2 to 12 in Appendix 1). F2 folds become more strongly defined below the 12 Level and are particularly well developed between the 23 and 27 Levels (e.g. Figure 5.10, contained in separate map folder) where they can be resolved into two main northeast plunging structures; the North Mine Antiform (NMA) and the North Mine Synform (NMS).

Intense shearing (probably D3A) destroys all fold geometry below the 29 Level to the 34 Level (having analogous effects to the Thompson Shear in the upper mine levels) and at depth below the 36 Level. Well-defined F2 folds come into prominence again in the Fitzpatrick Orebody on the 36 Level (e.g. see map NTH36 in Appendix 1).

**Junction Mine folds.** Fold geometries are suppressed in the upper levels of the North, Junction and Junction North Mines. Shearing, transposition and attenuation associated with the D3A Thompson Shear has destroyed or severely modified any remaining D2 fabrics (see below). Remnant isoclinal folds may remain as buckles and swellings in 3L in an otherwise strongly planar ore zone (see maps NTH2 to 12 in Appendix 1). An intensely transposed isoclinal antiformal hinge is preserved in 2L and may represent the up plunge equivalent of the North Mine Antiform (see below)

**North Mine Antiform & North Mine Synform.** The North Mine Antiform (NMA) and the North Mine Synform (NMS) become resolvable fold structure below the 12 Level of North mine. A third companion antiform is located on the southern margin of the 3L, to the south of the NMS but is an indefinite fold structure, being mostly destroyed by transposition. This structure will be referred to as the North Mine Southern Antiform.

The North Mine folds are a steep northeasterly plunging triptych of south verging asymmetric "Z" style isoclinal folds. They have thickened hinges and transposition is

focussed in common limbs and intensely developed throughout the host gneiss sequence surrounding the orebodies. The North Mine folds are mainly defined by the 3L and 2L orebodies, chiefly the former with form surfaces in adjacent metasediments remaining parallel to the orebody contacts, but also reflecting the transposition of the host gneiss sequence (e.g. Figures 5.10 & 4.22 to 4.24, see maps NTH22 to NTH30 in Appendix 1). 2L comprises a major part of the hinge of the NMA.

3L is weakly transgressive of the fold hinges, migrating from the northern antiform across the synform to the southern antiform with depth in the mine. By the 20 Level, the northern antiform has faded or been transposed and the 3L orebody lies largely within the keel of the NMS. 2L, though mostly transposed into a tabular sheet, lies within the transposed keel of the NMS for much of the plunge extent between the 15 to 18 Levels (see maps NTH12 to NTH22 in Appendix 1).

3L sulphide dominated ore contains a strong galena-defined S2 axial planar foliation that is parallel to the axial plane of both the NMS and NMA. Throughout the S2 fabric of the 3L ore are found abundant gem quality rhodonite and spessartine crystals that are unstrained. These minerals are still distributed through the ore in a distinct layer that is interpreted to reflect an original S0 gangue distribution (Figure 5.10 & see also Figures 4.22 to 4.24, see also Chapter 4). Gem quality rhodonite and garnet crystals are unstrained and un-deformed and therefore considered a syn-D2 fabric of the 3L ore. 2L is mostly attenuated and transposed and lies almost completely within the strong syn-D2 transposition fabric.

**The Fitzpatrick Synform.** The Fitzpatrick synform is the predominant F2 fold structure defined by 3L and 2L in the Fitzpatrick Orebody of the deep North Mine and comes into prominence below the dislocation of the Globe-Vauxhall Shear Zone (D3A, D3B, see below) between the 30 and 36 Levels (see maps NTH28 to NTH36 in Appendix 1). It persists and is the most significant geometric influence on the Fitzpatrick orebody until it is truncated at depth by the Western Shear (see maps NTH36 to NTH40 in Appendix 1).

The FS is the most intact fold structure in North Mine and comprises a tight north plunging synform that lacks the severe attenuation and isoclinal fold style of the NMA and NMS in the upper mine levels. Its relationship to these structures is uncertain but

the mineralogy of the ore and the style of the fold are consistent with its formation as a D2 fold.

#### 5.5.2.6. *Second order F2 folds in the Southwestern Region.*

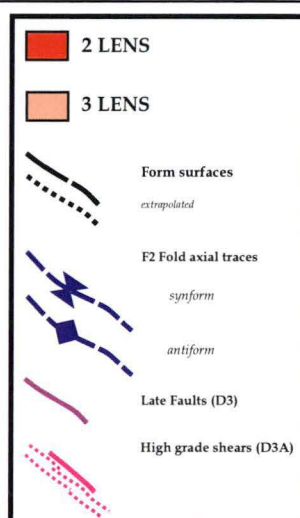
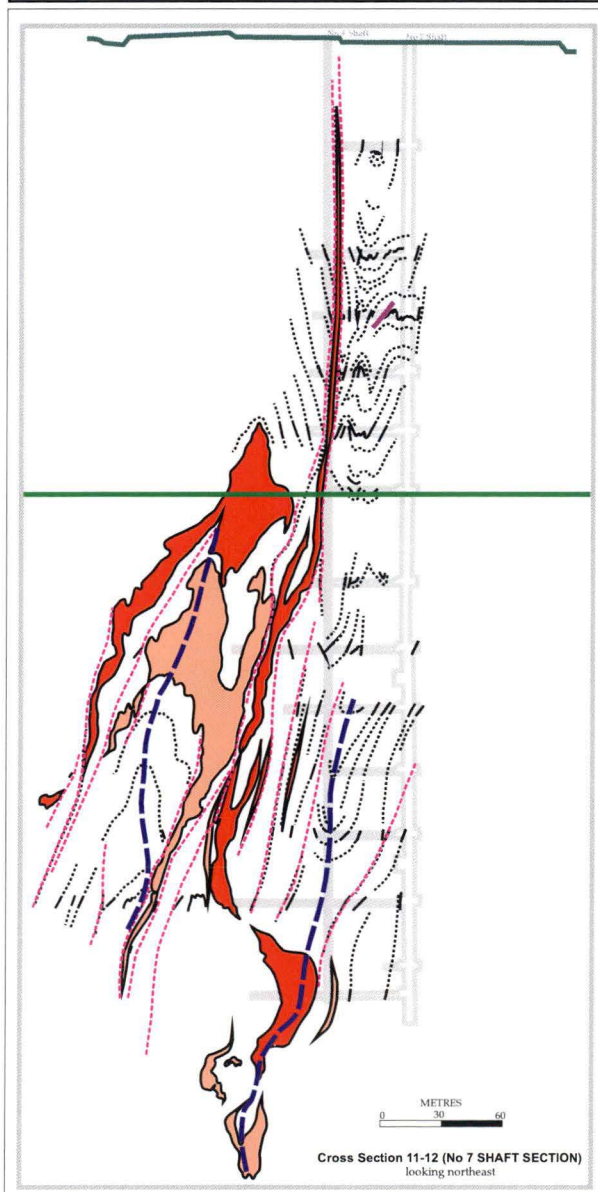
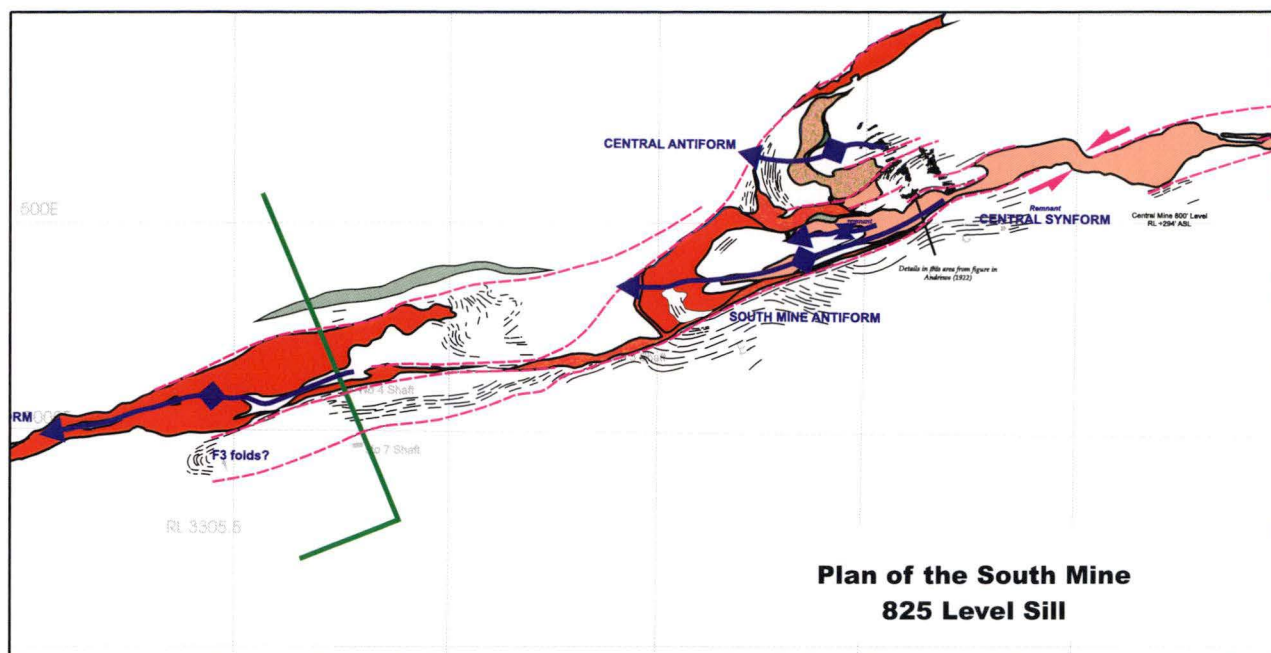
Second order F2 folds have a much steeper plunge than the overall general southwest plunge of the orebodies throughout the southwestern part of the field. Their plunge is generally steeper and possibly slightly more to the northwest (clockwise) than the plunge of the orebodies. The most important second order F2 folds in the southwest end of the mining field are described below.

**The South Mine Antiform, Central Mine Synform & Central Mine Antiform.** A fold triplet comprising two antiforms and a synform dominate the orebody geometry of 2L and 3L in the Central and South Mines. The antiforms; known, as the Central Mine Antiform (CMA) and the South Mine Antiform (SMA) are southwest plunging tight folds with rounded hinges and attenuated limbs and are separated by a small unnamed synform of variable amplitude. In many respects, the SMA and CMA could be regarded as a single complex fold closure (Figures 5.20, 4.25). They are asymmetric open to very tight folds throughout the Central and South Mine area but the CMA diminishes in amplitude down plunge to the southwest, as the SMA develops and comes into prominence. The exact relationship between the SMS and the ZC Antiform and NBHC Synform is difficult to determine exactly because the upper part of the ZCS is strongly attenuated and offset from its original position.

The Central Mine Synform (CMS) lies to the southeast of the SMA. The style of the synform is difficult to determine because it has been severely attenuated (D3A) and sheared and little of the original fold geometry remains. It now occurs as a large lenticular mass in the planar "Main Shear" (see below) that borders the southern side of the mines (Figure 5.20).

**ZC Antiform.** The ZC Antiform (ZCA) is known as the Western Antiform by Pasmenco mine geologists. It was recognised to be more complex than just a simple fold closure in the deeper mine levels by Webster (1993, 1994a), from whom some of the following description is derived.





**Figure 5.20** Level plan and cross section showing F2 fold styles within the orebodies in South Mine.

It is in this region of the deposit that 2L becomes the larger of the two main orebodies. Fold hinges preserve large masses of ore, while the limbs of F2 folds are attenuated and the oroboides thinned. The southeastern margin of the orebodies are severely attenuated by the D3A Main Shear.

The green line on cross section 11-12 shows the position of the 825 level. The green line on level-plan 825 shows the position of the section.

**Figure 5.20**

	<b>The Structure of the Broken Hill Lead Zinc Silver Deposit</b>	
<b>F2 FOLD STYLES IN SOUTH MINE</b>		
Data Sources: Various sources	Interpreted from Geol. Surv. (1935)	Author: A (Tony) E. Webster

The ZC Antiform first becomes recognisable near the South Mine – Pasminco Mine boundary, around the 625 Level of the South Mine (Figure 5.20 & 4.25). It persists throughout the latter mine to at least the 22 Level and is the most important influence on the geometry of 2L in this part of the deposit (e.g. Figures 4.9, 4.11, 4.15, 4.20). Within 2L, the ZCA changes in style from a very tight to isoclinal attenuated structure, to a broad, tight fold, down-plunge from the upper levels of the northeastern part of the ZC area.

Throughout its down-plunge extent, the ZCA is dissected to varying degrees by D3A shearing, especially between the 11 and 18 Levels, where the hinge is offset in a sinistral sense by approximately 100 metres (e.g. see map NBH17 in Appendix 1). Shearing and attenuation of the original fold geometry are particularly severe within the clastic metasediments, 2L and 3L. The shearing offset has a particular effect within 3L in the hinge of the fold and it is dismembered. The ZCA persists within the Garnet Quartzite Horizon where the geometry is simpler, being less affected by shearing, though dislocations are present.

In the 19 to 20 Level area of the Pasminco Mine, within 2L, the geometry of the ZCA hinge zone is largely a product of the effects of D3A sinistral attenuation and shearing along the southern and northern margins of the greatly thickened 2L orebody within the fold. The hinge region is interpreted to have originally consisted of a series of mesoscopic antiform/synform pairs within the ore, comprising the macroscopic antiform. The mesoscopic folds have been merged together by attenuation and the antiformal shape accentuated (See maps NBH18 to NBH20 in Appendix 1). On the 19 and 20 levels, within 2L, elements of the more open style antiformal shape is still well preserved, though the southern and northern margins are intensely sheared (Webster, 1993). The ZCA is well defined in 1LU and 1LL on the 17 and 18 Levels of the mine where the orebodies define a very tight angular fold with straight limbs (see Figure 4.20).

Prior to D3A shearing and attenuation, the ZCA developed within 2L was a very tight structure in the upper parts of the mine and a more open, rounded and gentle fold in the deeper levels. The down-plunge change in style probably reflected the greatly increased thickness of 2L.

**NBHC Synform (Pasminco Mine).** This fold is known as the Eastern Synform by geologists in the Pasminco Mine (e.g. Webster, 1993, 1994a). The NBHC Synform is an isoclinal, partly 'tear-drop' shaped, south-westerly plunging F2 fold that occupies the southern margin of the NBHC area of the Pasminco Mine. It is the predominant influence on the orebody geometry of the southern part of 2L, 1LL and 1LU on the 18, 19 and 20 Levels and on ALL between the 10 and 18 Levels.

In all parts of the mine where the NBHCS is developed in 2L and clastic metasediments, it has been extensively modified by D3A attenuation and the limbs are drawn out and 'stretched'. Adjacent marker horizons in the metasediments, such as amphibolites and Potosi type gneiss units, are also drawn out, attenuated, boudinaged and dislocated. However, the 'underwall zone' stratigraphy and orebody stratigraphy usually remain intact in the hinge region of the fold (e.g. Figure 5.7 & 4.9). Attenuation may be so intense that 2L, and to a lesser extent 1LL, may only be represented by thin sheets and lenses of ore and lode rocks. The fold is better preserved where it is developed in the Garnet Quartzite Horizon hosting 1LL and 1LU.

The NBHCS has a particularly strong influence on the geometry of ALU below the 14 Level, which mostly lies within the keel of the fold in this area. This tightly infolded position has caused intense D2 to D3A dislocation in the Garnet Quartzite Horizon, which was associated with extensive syn-D2 to D3A sulphide mobilisation. Where the GQH occupies the keel area, extensive dislocation of the unit has taken place and it is displaced as a series of slices (see section 5.5.3.2; see also map NBH10 to NBH18 in Appendix 1).

The original style of the NBHCS developed in the clastic metasediments hosting 2L and 3L is difficult to determine due to the extensive shear modification it has undergone. However, it is better preserved within some parts of the Garnet Quartzite Horizon, particularly between the 11 and 14 Levels of the Pasminco Mine. In this region, it is a tight to open style fold with straight limbs (see maps NBH11 to NBH14 in Appendix 1).

**The Western Keel Synform.** The Western Keel Synform (WKS) is defined within both 2L and the Garnet Quartzite Horizon (GQH) hosting A Lode Lower to the north of the ZC Antiform (Webster, 1994a). Post-folding D3A attenuation within the belt of clastic metasediments between ALL and 2L has dislocated the hinge zone of the WKS where

it lay within the two separate orebodies and subsequent modifications have changed the nature and shape of the fold in the dismembered segments. The effects of the F2 folding were also considerably different in the GQH to those within 2L and its enclosing clastic metasediments (see below). The following description of the WKS in 2L is mainly drawn from Webster (1994a)

On the northern margin of 2L, the WKS is defined by the distribution of various styles of mineralisation, gangue and foliation traces preserved in the ore. They define a strongly 'boat shaped' part of 2L forming a shallow doubly plunging synformal keel. Zones of rhodonite, vein brecciated rhodonite and pyrrhotite are arranged symmetrically along the centreline of the keel and the symmetry in the disposition of these ore types mirrors the wall rock contacts. The trace of carbonate banding also defines small, tight folds with orientations that parallel the long axis of the WKS and dip inwards towards the centre of the synform on both the eastern and western margins. Banding within the orebody is concordant with that in adjacent metasediments.

Within the metasediments below 2L, the WKS comprises a series of asymmetric, westerly dipping chevron folds that are the product of D3A transposition and folding. The median surface of these folds defines the larger keel of the synform. The axial surface of WKS dips at approximately 40-45 degrees west in the NBHC area but steepens to the north. D3A accentuated and modified a mesoscopic F2 synformal fold keel and the present form of the structure can be partly regarded to be the result of the accentuation and re-orientation of the original F2 synform and D3A shearing.

A muscovite-defined S3 foliation parallels the axial surfaces of small-scale parasitic D3A folds. S3 is most strongly developed in sub-centimetre bands and fine foliae, usually along planes of metasedimentary banding that are offset from the fold hinges. This foliation is interpreted to be a later D3B fabric overprinting the more intense D3A transposition and folding (see below). The relationship of the quartz-muscovite-biotite fabric (D3B) to the intense marginal transposition and development of the WKS is unclear. In most areas the muscovite fabric appears to be imposed on an earlier D3A (biotite and sillimanite) fabric and propagates along existing geological surfaces (such as transposed layers and fold limbs). Down dip from the orebody termination, the D3A transposition and folding rapidly fades in intensity to become a weak retrograde foliation that is sub-parallel to metasedimentary banding. In the northeastern part of

the Pasminco Mine, the WKS becomes more intensely transposed and shear-like, eventually merging with the WZS (see below).

In the GQH hosting ALL, the WKS is a tight, slightly asymmetric “V”-shaped fold within which abundant siliceous blue quartz-garnet-galena-sphalerite vein systems have formed in the hinge region adjacent to the mineralised horizon. The geometry of the structure is best defined on the 16, 17, 18 and 19 Levels of the Pasminco Mine (see maps NBH16 to NBH19 in Appendix 1).

**The Southern Cross Antiform & the Southern Cross Synform.** The Southern Cross Synform comes into prominence within the GQH and Southern 1L in the Southern Cross Shaft area of the Pasminco Mine. This structure has not been assessed in detail, because it mostly lies below the 21 Level of the Pasminco Mine, which is the limit of the current study on the southwestern end of the field. However, some comments can be made about the fold between the 18 and 21 Levels where the folds first become obvious.

The SCS hosts Southern A Lode and Southern 1 Lens within a shear-isolated infolded mass of garnet quartzite and lode rocks. The hinge of the fold has been isolated by shearing and extreme attenuation and is almost ‘tear-drop’ in cross sectional shape, such as is shown on Mine Section 105 (Mackenzie & Davies, 1990) (see maps NBH20 and NBH21 in Appendix 1).

SAL is strongly sheared and retrogressed along the eastern contact within the Southern Cross Synform and it is cut obliquely by a northwest dipping shear and fracture zone carrying calcite and secondary manganese minerals (Mackenzie and Davies 1990).

### **5.5.3. Relationship of Early Orebody Geometry to D1 and D2 Structures.**

In the Pasminco Mine, 3L, 2L, 1LL, 1LU and ALL transgress F2 fold hinges from southwest to northeast with depth on the mine. In successive level plans the main mass of these orebodies can be seen to occupy progressively more northwesterly positions, changing from the southeastern limb and then through the keel of the NBHCS; crossing the hinge of the ZCA and either terminating on the northwestern limb of the ZCA or persisting into the WKS on the 19 Level (e.g. Figure 5.15). The

relationship between F2 and the elongate orebody geometry is also preserved in 3L in the North Mine, where the S0 distribution of rhodonite, fluorite and primary quartz is still transgressive of F2 fold axes (Figure 5.10, in separate map folder). It is harder to demonstrate the same relationship conclusively in the central part of the mining field because of the intensity of D3A shearing (see below) but there is some evidence to support it in the Block 14 and British Mines where 3L containing the rhodonite layer is transgressive to the F2 fold axes (Figure 4.26). This observation shows that 3L, 2L, 1LL, 1LU and ALL were elongate, lenticular bodies (prolate ellipsoids) prior to D2 and it shows that the high aspect ratio of these orebodies predates D2.

The geometric relationship between the strike of the essentially linear mineralised system and its contained orebodies, and second order F2 fold axes, also supports the view that this is not the primary cause of the elongate shape of the orebodies. Thicker regions of orebodies migrate across fold hinge zones and are not just thickened within them. This observation is further supported by the geometric relationship between the lens-like, elongate horizons in the LodSeq, such as the GQH, and the other elements of the MinSeq, which show a similar transgressive relationship to F2 fold axes. Stratigraphic relationships within the MinSeq must have been established prior to F2 folding. F2 folds not only deform the orebodies but they also fold the units of the Lode Sequence and all other elements of the MinSeq, including the transgressive syn-D1 lode pegmatite dykes that intrude it.

The apparently thicker mineralised positions observed within antiformal hinges in some orebodies in the Pasminco Mine, such as the rollover position within ALL, are simply the point at which the stratigraphically thickened central region of the ribbon-like orebodies (prolate ellipsoids) migrate across second order F2 hinges. Fold limbs tend to be preferentially thinned by post D2 shearing and attenuation, further enhancing the relative thickness of fold hinges. Sulphides have not been structurally mobilised into F2 fold hinges. It is also important to note that if sulphides had been structurally mobilised into F2 hinges, then calcite, silicates (including pyroxenoids) and other gangue constituents of the ore would also have to have been mobilised into such structural sites in a similar manner. These minerals make up a similar proportion of the orebodies in fold hinges as they do in fold limbs and the integrity of the internal stratigraphy of the orebodies is preserved.

The apparent thickening of the ore that is observed in F2 fold hinges is highly variable and is mainly mechanical in origin. There has been little preferential sulphide enrichment within antiformal hinges during D2. Exceptions are the mobilised sulphides that now form part of the vein systems adjacent to some ore lenses in the Garnet Quartzite Horizon and within the silicified metasediments adjacent to 2L and 3L in North Mine. Only in the northeastern part of the mining field, where F2 folding was most intensely developed, was there significant sulphide mobilisation associated with F2 folds. This took the form of a sulphide redistribution, which formed a galena-defined S2 axial planar fabric in 3L (Figures 5.10 and 4.22 to 4.24).

D1 seems to have had little effects within the orebodies and MinSeq. There is no evidence for an S1 fabric in the ore. The often finely interbanded silicate, calcite (+/- apatite and fluorite) and sulphide banding of the orebodies is unlikely to have developed from a syn-D1 metamorphic differentiation process because of the mineralogical diversity of the constituents of the banding, especially in 2L and 1LL (see section 5.4.3). Banding within the orebodies is also transgressed by early pegmatite intrusives (Webster, 1993; 1994a), which are in turn folded by F2. F1 folds are unknown in the mine area and have not been conclusively identified at a district scale. No syn-D1 shear fabrics are recognised in the mines area (see section 5.4.5) and there are no early structural inversions identified in the MinSeq, which might be evidence of F1 folding or shearing.

The evidence from the orebodies, Lode Sequence wall rocks and MinSeq stratigraphy strongly supports the view that the orebodies are largely in place, conformable with the surrounding stratigraphy, transgress F2 folds and have not been structurally mobilised on a massive scale during either D1 or D2. No structural or stratigraphic evidence has been found to support an interpretation of a structural original for the northeast-southwest elongation of the Broken Hill mineralised system.

#### 5.5.3.1. *Relationship of A Lode Lower to F2 folds.*

ALL represents an excellent example of the relationship between an elongate orebody and D2 folding. So, it is used as an example of the relationship between F2 folding and the orebody horizons (considered to be S0). Similar relationships have been observed in 2L (Webster, 1994a), 3L, 1LL and 1LU.



ALL extends from the 7 Level, where it lies within the southeastern limb of the NBHCS to the 20 Level, where it lies completely within the keel of the WKS. The orebody extends from approximately 100 mS to 1200 mS. The main mass of the mineralisation transgresses F2 fold hinges from east to west with depth on the mine. In successive stacked level plan interpretations it can be seen that the main mass of the ore migrates from the southern limb of the NBHCS on the 8 Level, crosses the keel of the NBHCS on the 14 Level and then the hinge of the ZCA on the 15 Level. It occupies the common limb of the ZCA and WKS on the 16 Level and lies completely within the keel of the WKS on the 19 Level (Figure 5.15). The migration of the orebody across these major F2 fold structures shows that the orebody plunges less steeply to the southwest than F2.

The main mass of ALL mineralisation is transgressive of the axial surfaces of F2 folds, such as the ZCA. The thickest part of ALL occurs within the keel of the NBHCS on the 14 Level of the Pasminco Mine but progressively migrates around its hinge, and eventually through the hinge of the ZCA down plunge to the southwest. On the 19 Level, the main mass of ALL lies within the synformal keel of the WKS. This observation suggests that the strike of the axial surfaces of F2 folds was mildly transgressive of the original strike of ALL mineralisation, as has been shown for 2L (Webster, 1994a). The ALL rollover position (which was mined as the 'Rollover stope') is actually the position within AL where the main transgressive mass of AL mineralisation crosses the hinge position of the ZC Antiform. A similar relationship is seen with the 1L Group, 3L and BL.

The keel position of the WKS within ALL on the 19 Level is correlated with the early F2 WKS in 2L and 3L. Post fold sinistral offset has taken place along the D3A WZS (Webster 1994a) and its related structures. The WKS in ALL is now offset by several tens of metres to the southwest relative to the WKS part of the structure defined by 2L. Subsequent shearing has more strongly affected the WKS within 2L.

The intersection line of ALL and the crosscutting F2 folds define a lineation that plunges approximately 70° west-southwest, whereas the ore lens itself plunges southwest more shallowly, at 20° to 30°. This crosscutting relationship clearly shows that there is no relationship between the elongation of ALL and the hinges of F2 folds, as might be produced were the orebodies formed within structural sites. The ribbon-

like form of ALL, and the rhodonite horizon within it, was established before F2 folds formed.

There has been no structural control on the elongate form of the ALL orebody. This geometry, the internal manganese pyroxene horizon, banding defined by primary quartz and sulphide-quartz abundances, and the stratigraphic relationships of the orebodies within the GQH all predate D1 pegmatite formation (anatexis). No mobilised styles of sulphides were formed prior to pegmatite intrusion, only during syn-D2 folding (F2), and to a lesser extent during later events. Therefore, the elongate form of ALL predates deformation and the peak of D1 metamorphism. Consequently, the recently suggested model of White et al., (1995) that considers the orebody to have been moved en-masse into a shear related fold hinge is not supported by the observed geology of ALL. This orebody clearly transgresses syn-metamorphic folds.

The importance of this relationship lies in the fact that it clearly illustrates that the ribbon-like form of the orebodies is a very early (probably primary) feature and is not related to F2 folding or later deformation. ALL provides a clear example of the distinction between the stratigraphic elongation of a Broken Hill orebodies and the overprinting structures associated with the Olarian Orogeny. The current geometry of ALL is the results of an interaction of the original geometry of the orebody with F2 folding and D3 shearing.

#### 5.5.3.2. *The Structure of A Lode Upper.*

The present geometry of ALU, and to a lesser degree A Lode Lower is determined by its position on the southern limb of, and within the keel of the NBHC Synform within the GQH. The orebody is relatively planar in the limb of the fold but strongly deformed within the keel.

Intense folding within the keel of the NBHC Synform has strongly modified the part of the mineralisation that is in the keel. Widespread, partly shear-hosted, sulphide mobilisation and developments of quartz-sulphide-silicate breccia zones are widespread in the ore horizon and adjacent garnet quartzite in the hinge zone. Shearing and sulphide mobilisation is focussed in planes between dislocated 'blocks' of the Garnet Quartzite Horizon, which has been fragmented during folding (e.g. see maps NBH14 to NBH18, in Appendix 1). D3 shearing, which is preferentially

developed within the common limb of the NBHCS and ZCA, has further emphasised the elongate, truncated and asymmetric form of the orebody.

### **5.5.3.3. *F2 folding of lode pegmatite.***

The transgressive intrusive relationship between lode pegmatite and the GQH & BLH is folded by F2 folds, such as the ZCA and the SXA, so is pre-D2. The intrusion of pegmatite post-dates the establishment of the MinSeq stratigraphy and the ribbon like geometry of the orebodies, Garnet Quartzite Horizon (GQH), 4.5 Horizon and B Lode Horizon mineralisation was established prior to pegmatite intrusion. It has been suggested above that the weakly developed D1 deformation is mainly defined within the mineralised system by the intrusion of pegmatite into the pre-existing strata of the Lode Sequence. Therefore, the geometry of the orebodies and their associated stratigraphic package is very early, has not been produced by D2 and was established prior to the peak of regional metamorphism (M1).

### **5.5.4. Mass Movement of Sulphides into F2 Fold Hinge Zones.**

Investigations of the internal fabric of the BH orebodies are few (eg. Hodgson, 1967; Maiden 1972; Webster, 1993; 1994a), yet many authors have inferred processes that involve the preferential mass movement of sulphides into fold hinges at BH during deformation (most recently Rothery, 2001). Such workers rarely provide evidence to support their assumptions, except to note that mine cross sections show that orebodies are thicker in fold hinges relative to fold limbs. However there is abundant information in mine records, in the form of lead grade mapping and gangue distribution mapping (e.g. Figures 5.10 & 4.22, 4.23, 4.24, 4.36, 4.37,) that reveals the internal structure and fabric of the orebodies within such hinge regions. These data show that the preferential mass movement of sulphides into fold hinges is very unlikely to have occurred at BH. Instead, the data show that there has been a structural redistribution of some elements of the ore during deformation (chiefly galena) to produce a well-defined S2 axial plane foliation. Gangue minerals retain a stratiform distribution in even the most intensely folded parts of orebodies (see Chapter 4). The orebodies are, in some cases, thicker in the hinges but within these zones, the stratigraphy is preserved and all the gangue minerals are also thicker. The internal structure of the orebodies shows that there has been a pervasive redistribution of galena in the northern part of the deposit but only relatively minor and localised

amounts in the southwest part of the deposit. While there is no fractionation of ore minerals from gangue towards the hinges, the shape of the orebodies reflects their angular relationship to S2 and this gives a higher thickness to width aspect when orebodies occur in F2 hinges.

Mobilised sulphides are generally rich in re-crystallised primary gangue components such as rhodonite and bustamite (3L, 2L, ALL), particularly in the North Mine. Hedenbergite, wollastonite and knebelite (olivine) are also commonly found within mobilised sulphides or calc-silicate mineralisation that is associated with them (mainly 2L and 1LL). The two-pyroxene mineralogy of most mobilised sulphides, which overprints the earlier annealed banded texture (S0) and stratigraphy of the orebodies and wall rocks, shows that they formed at granulite grade. The distribution of mobilised sulphides is also spatially associated with F2 folds (and associated shearing). Therefore, the most significant sulphide mobilisation within the BH orebodies took place during D2 (Webster 1993, 1994a).

Fabric defined by mobilised sulphides highlight the effects of deformation within the orebodies and adjoining rocks and provide several lines of evidence that show that F2 folding took place within the orebodies during granulite grade regional metamorphism. This evidence includes:

- In the northern part of the deposit, sulphide mobilisation was pervasive throughout 3L and produced a strong lead-grade defined S2 fabric within the orebody. The S2 fabric overprinted the stratiform gangue distribution and is parallel to the axial planes of the NMS and the NMA.
- Sulphide mobilisation within 3L in the Northern Mine resulted in the intense invasion of the rhodonite masses where they were infolded into the keels of F2 folds. The rhodonite zone within the orebody was heavily impregnated by fluid-phase mobilised sulphides leaving only remnant pipe-like bodies of un-mineralised rhodonite preserved in F2 fold keels (where it had been thickened during F2 folding). Rhodonite was re-crystallised within the mobilised sulphides. In the Pasminco Mine, sulphide mobilisation was more tightly constrained within litho-structural sites (especially the margins of rhodonite masses) and was not pervasive (Webster 1993, 1994a).
- Folded bodies of rhodonite in F2 fold hinges within 2L and 3L are coarsely re-crystallised around the margins, with re-crystallised rhodonite being intergrown with coarsely crystalline sulphides, bustamite, calcite, hedenbergite, wollastonite and olivine (Webster 1993, 1994a).
- In 3L in the North Mine, rhodonite occurs as individual rounded crystals that are disseminated throughout coarsely crystalline, equigranular sulphides, which

makes up the bulk of the orebody in this area. Superbly crystallised rhodonite and spessartine garnet also occur, often abundantly, within 3L within otherwise sulphide dominated ore that preserves the galena-defined S2 axial planar foliation.

- Hedenbergite-garnet-(bustamite)-blue quartz-bearing stockwork vein systems occur within garnet quartzite adjacent to orebodies contained within the GQH where F2 folding was most intense, such as in the fold keels of the WKS and NBHCS in the Pasminco Mine (Figures 5.21 & 5.22).
- D3A shears overprint F2 folds, D2 styles of mobilised sulphides and the associated gangue mineral textures. D3A shears are focussed within F2 keels (e.g. ALL within the NBHCS) and syn-D3A fabrics overprint those of D2. See below.

The textures and lithological relationships of mobilised sulphides, primary silicates and calcite within the orebodies show that two processes of sulphide mobilisation operated during D2. The first process was dominated by the mobilisation and transport of sulphides in solution (or possibly melts), which were then deposited in litho-structural sites (Fluid-Phase Mobilisation). The second process was dominated by the in situ re-crystallisation during flow of the sulphide and gangue components of the mineralisation (Mechanical Mobilisation). The two processes are discussed briefly below.

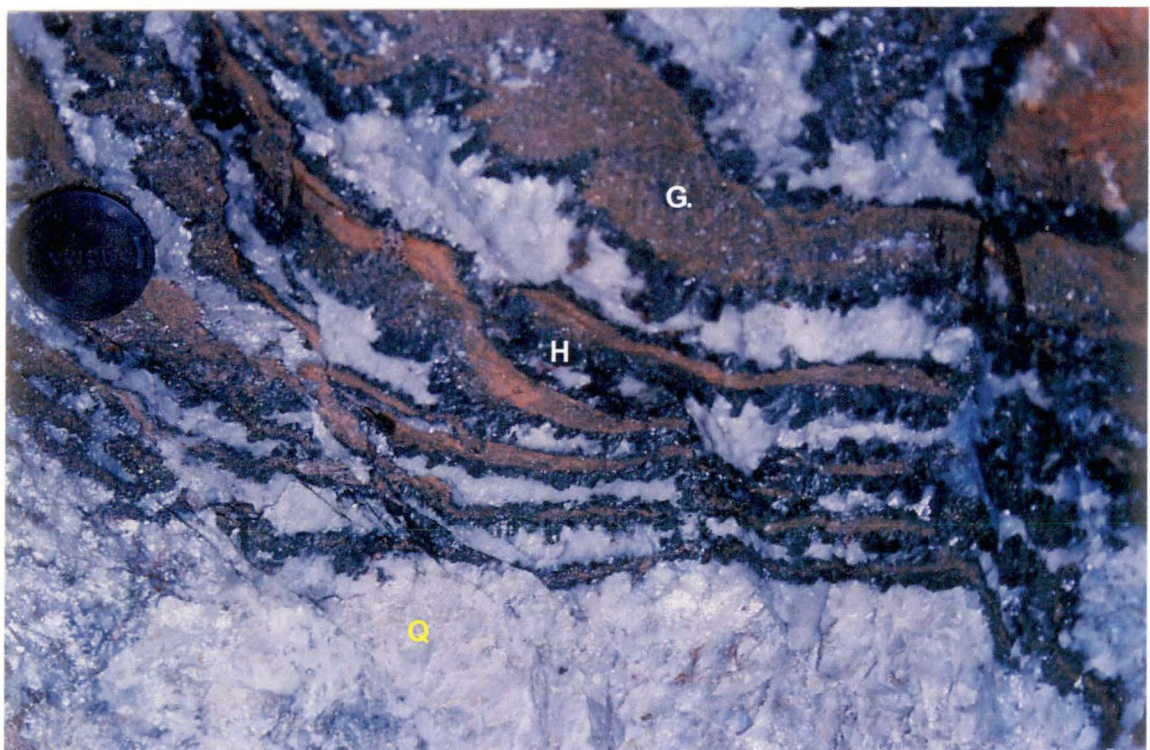
#### **5.5.5. D2 Fluid Phase Sulphide Mobilisation & Siliceous Metasomatism**

Fluid phase sulphide mobilisation is widely associated with D2 mobilisation of orebody sulphides and the evidence for it lies in the many silicified zones, quartz-sulphide-silicate breccias (often lined by hedenbergite), siliceous sulphide vein systems, coarse-grained sulphide veins and re-crystallised gangue silicates that occur in deformed regions of the deposit. The generation of such zones probably persisted into the early stages of D3A (see below). Preferred sites of syn-tectonic sulphide precipitation were fractured and brecciated garnet quartzite adjacent to ore lenses within F2 fold hinges (Figure 5.21 & 5.22), garnet sandstone at orebody contacts (Figure 4.13) and clastic metasediments at orebody contacts. In the latter, S0, S1, transposed S0 and S2 banding and schistosity were replaced (Figure 4.10). Fractures and breccias produced in rocks that remained competent but failed in a brittle manner during D2 folding (e.g. garnet quartzite, psammite and pegmatite) and competent rock types within orebodies (e.g. rhodonite layers) were preferred sites of mobilised sulphide precipitation during D2. Fluid phase mobilisation also produced





**Figure 5.21.** Quartz-hedenbergite veining developed in garnet quartzite adjacent to the 'toe' of A Lode Lower ('Western A Lode') within the keel of the Western Keel Synform (17 Level Pasminco Mine) Folds are probably F3 (early D3A but could also be F2). Pink = fingerained garnet (garnet sandstone after garnet quartzite); dark green = hedenbergite rimming quartz veins; white = white quartz veining. See below for details.



Close-up view of the veining with F3 (F2?) Folds. G = fingerained garnet (garnet sandstone after garnet quartzite); H = hedenbergite rimming quartz veins; Q = white quartz veining. See above for location of this photograph (red outline).

disseminated styles of sulphide enrichment by replacing gangue constituents (especially calcite) of stratiform mineralisation. Within the GQH fluid-phase sulphides produced widespread vein and stockwork systems adjacent to orebodies (e.g. Webster, 1993 & 1994a; Prendergast, 1995; Prendergast et al., 1998).

Siliceous metasomatism was widespread at the margins of the orebodies and within adjoining wall rocks during D2 and D3A (Webster 1993, 1994a). The interaction between siliceous fluids, carbonate and manganese silicates within ore lenses formed a suite of distinctive metasomatic styles of mineralisation containing variable amounts of hedenbergite, wollastonite, knebelite, bustamite, quartz and garnet. Silicification was also strongly developed within garnet quartzite in association with stockwork vein formation and clastic metasediments were intensely silicified at ore-wall rock contacts (especially in the northern part of the deposit).

D2 siliceous metasomatism was most strongly developed in the northeastern part of the mining field where large-scale sulphide mobilisation and silicification occurred at the margins of 3L and between 3L and 2L in all areas of North Mine. A broad siliceous mineralised halo was formed around 3L and was particularly well developed in the footwalls of both 2L and 3L. Siliceous alteration overprints the folded fabric of the metasediments in places (Figure 5.10c & Figures 4.22, 4.23 & 4.24, all in separate map folder). The event has affected a zone that extends from approximately the central British Mine to the Fitzpatrick Orebody and although variably developed, is a remarkably consistent feature of this part of the field. The orebodies have suffered extensive and quite intense contact silicification that has strongly altered the contact metasedimentary wall rocks. Wall rock bedding and transposed bedding are overprinted by blue quartz and sulphide alteration but the layering is preserved.

This process has formed large zones of low to high-grade siliceous blue quartz lode of mineable grades that were not originally part of the orebodies. Metasedimentary banding within adjacent clastic metasediments can be traced by mapping from unaltered metasediments into the low-grade siliceous ore zones. Sulphides migrated into the zones of blue quartz silicification, (Figure 5.10c & Figures 4.22, 4.23 & 4.24), often in narrow bands paralleling the original bedding but more often as medium to coarse-grained veining and veinlets (Figure 4.10d & e). Sulphides have been mobilised during the process and have 'mineralised' the wall rocks, to such an extent in many places that the alteration halo was mined as low-grade siliceous ore by the North





**Figure 5.22a.** Blue and white quartz, +/- sulphide breccia in F3 (?) folds in garnet sandstone (altered garnet quartzite) within the Garnet Quartzite Horizon, 17 Level 'Western' A Lode, Pasminco Mine. Field of view approximately 1.5m. SS= garnet sandstone. bq = blue quartz veining.



**5.22b.** Late stage quartz-galena-sphalerite +/- pyrrhotite, +/- chalcopyrite vein cross cutting hedenbergite veined and altered garnet quartzite (now garnet sandstone). 'Western A Lode' 17 Level, Pasminco Mine. Rock bolt plate is approximately 30cm long.

Mine. Alteration overprints the transposed banding in metasediments in zones of the most intense folding and therefore developed late in D2. It probably persisted into early D3A (Figure 4.10).

In the North Mine No 1 open cut, distal 2L mineralisation is associated with a well-developed metasomatic alteration zone consisting of pale creamy-pink garnet-quartz rock known locally as 'GO' rock. GO rock is particularly well developed on the up-dip margins of the ore zones (D Larsen pers comm., 1993; Lips 1994; White et al., 1995 and Larsen and Webster, 1996) and reflects metasomatism along the orebody margins during D2 folding and transposition.

Siliceous alteration and mobilised mineralisation was also strongly developed along the attenuated southern margins of 2L, 3L, 1LU and 1LL during D3A in the Pasminco Mine. D3A alteration resulted in a suite of characteristic ore types described as "Saccharoidal Mineralisation" within 2L and 1LL/1LU by Webster (1994a (his "G2A" event)). Extensive zones of metasomatic mineralisation were developed within litho-structural sites in the GQH adjacent to the orebodies, particularly within F2 folds and within D3A shears (discussed below). Similar blue quartz-dominated styles of low grade sulphide mineralisation to those adjacent to the North Mine orebodies are seen adjacent to BL in the Southern Cross area of the Pasminco mine where sulphide veining and migration has occurred in wall rocks that have been altered to siliceous and blue quartz-bearing lode-like rocks. Lode pegmatite is often mineralised in this way, such as on the 16 and 17 Levels (Figure 4.10b).

Large-scale alteration and silicification of garnet quartzite, has taken place along the contacts of ALL where it is tightly infolded and dislocated within the keel of the NBHC Synform and Western Keel Synform on the Pasminco Mine (e.g. Figure 5.21 & 5.22). ALL was traditionally a difficult orebody to reconcile mill returns with stated ore block reserve grades predicted by ore resource calculations. Sulphides have been moved on mass to into narrow shear zones, breccia systems and stockworks within the brittle garnet quartzite. Similar zones have been described in detail in Western A Lode by Prendergast (1996) and Prendergast et al., (1998)

D2 (D3A) siliceous metasomatism resulted in widespread alteration of mineralisation and wall rocks at orebody contacts. It was best developed in zones of isoclinal F2 folding and D3A shearing and was associated with the formation of the



metasomatically altered styles of mineralisation (Webster, 1994a). Extreme degrees of structural dislocation and shearing took place within ALL in the keel of the NBHCS and these zones provided environments for sulphide mobilisation, silicification and resulted in a pervasive redistribution of the stratiform ALL ore into vein and shear systems. This caused the problems with grade estimations in the past (ore resource models broke down when using stratiform layer assumption models). The quartz-hedenbergite vein systems in Western A Lode were also formed during the same event. Sulphide mobilisation and silicification processes persisted into D3A.

The formation of garnet sandstone, by the alteration of garnet quartzite, took place during D2 (Figure 4.12), in association with extensive sulphide mobilisation (chiefly galena), quartz veining and hedenbergite crystallisation. Alteration of garnet quartzite persisted into D3A. However, the main developments of garnet sandstone were present prior to D3A because clasts of garnet sandstone are incorporated into massive pebble ore zones formed from attenuated 1 Lens mineralisation on the 22 sub-level, Pasminco Mine. The zone on 20 Level of the same mine has been folded during D3A, after vein formation. Narrow zones of the clastic metasedimentary rocks adjacent to most orebodies were also affected by syn-tectonic metasomatic processes that generated garnet and the 2cm-1m wide garnetiferous 'rinds' that are so common on most contacts of 2L (e.g. upper contact of 2L in the Pasminco Mine) were the result. It is probable that these processes continued into D3A as there are garnetised rinds on 2L and 3L within the heavily attenuated southern limb of these orebodies between the 20 and 24 Levels.

Similar low-grade siliceous blue quartz-sulphide mineralisation to that forming a halo in the North Mine orebodies was also developed on the contacts of 2L and 3L in the Pasminco Mine. However, it is generally spatially associated with zones of D3A shearing and transposition at this end of the mining field. In such zones, the siliceous blue-quartz mineralisation is observed to overprint the banded texture of transposed metasediments.

McGunnigle et al., (1998) recognised that structurally mobilised sphalerite-dominated ore in the Potosi Orebody was enveloped in a blue quartz alteration halo that contained variably disseminated galena, pyrrhotite, pyrite, chalcopyrite, sphalerite, gahnite and garnet. The mineralisation was reoriented to lie parallel to the axial surface of an F2 synform.

Wall rock alteration persisted into D3A, associated with the extensive development of saccharoidal mineralisation (characterised by sugary quartz), and variably developed hedenbergite and garnet in association with wall rock silicification (Webster 1993; 1994a). Blue-quartz-sulphide stockworks and variably developed pegmatitic galena veins occur within the GQH adjacent to orebodies, particularly in intensely folded regions where the competent, brittle nature of the garnet quartzite resulted in fracture systems that formed sinks for mobilised sulphides and siliceous fluids. Extensive hedenbergite veining was also developed in some areas of ALL in association with silicification of the wall rocks and development of saccharoidal zones (e.g. Figure 5.23).

Within the orebodies at Broken Hill, wollastonite, hedenbergite, bustamite and the suite of less common calc-silicates are the products of intense but localised syn-deformational and structurally controlled metasomatism and largely post-date F2 folding. The styles of mineralisation formed during D2/D3A siliceous metasomatism lie at the contacts of the orebodies, especially where they have been highly attenuated. Saccharoidal quartz and/or calc-silicate mineralisation may be the only constituent of the orebodies in severely attenuated regions of 2L, 3L, 1LU and 1LL (Webster 1994a). Significant calc-silicate components are only found within orebodies with a significant calcite and/or rhodonite content.

Important styles of mineralisation developed within and adjacent to the main orebodies during D2/D3A include textural types that correspond to (from Webster 1993, 1994a);

- Saccharoidal (sugary textured) siliceous mineralisation,
- Quartz-hedenbergite-garnet vein stockworks,
- Blue-quartz and clear-quartz stockworks,
- Opalescent white quartz mineralisation,
- Low-grade siliceous blue-quartz mineralisation, and
- Blue quartz-sulphide alteration zones along orebody contacts, especially on the footwall of 3L in the North Mine.

Silver, gold, arsenic, tungsten and copper-rich mineralisation was formed in the garnet sandstone bodies adjacent to 2L on the 20 Level and 24 Levels of the Pasminco Mine (Webster, 1994a) and in the lower levels of the BHP Mine.

#### 5.5.5.1. *Alteration of D1 Lode Pegmatite Bodies during D2/3.*

Stratiform and mildly transgressive lode pegmatite bodies underwent widespread alteration during D2 and D3A, forming quartz pseudomorphs of feldspar crystals as well as hydrothermally shattered, brecciated and quartz-annealed zones along their margins. In thin (<2m) zones of pegmatite, where such processes took place, whole bands of pegmatite may now be aggregates of pseudomorphed feldspars and fine networks of quartz veining.

In the Southern Cross area, where lode pegmatite bodies are best developed within the GQH, mobilised sulphide mineralisation and associated siliceous and muscovite alteration was focussed along the margins of the lode pegmatites. This is especially well developed towards the southern end of BL where the greater competency of the pegmatite, and its resultant fracturing during D2, resulted in the localisation of the fluid-phase mobilised sulphides and the associated siliceous metamorphic fluid. Siliceous alteration of pegmatite was widespread and sulphide impregnation was common in proximity to mineralisation. At the southwest end of BL, in the Southern Cross area (where BL passes out of the GQH), one of the D1 lode pegmatite bodies lies close to, or transgresses the contact of BL. The contacts of the pegmatite have been extensively altered by D2 mobilised sulphides, and strongly affected by D2 silicification resulting in extensive alteration of the pegmatite mineralogy along its margins (Figures 5.5b & c). In many areas of southern BL it is very difficult to distinguish mineralisation within pegmatite and mineralisation within the orebody as the contacts between orebody and D1 pegmatite have been overprinted by D2 alteration and sulphide mobilisation. Apart from pegmatite-contact alteration by D2 mobilisation, siliceous alteration and mobilised sulphides have penetrated along fine fractures within the pegmatite, coarse feldspar crystal boundaries and even along cleavage planes of the larger feldspars crystals.

In all areas of lode pegmatite affected by D2 alteration and mineralisation, green feldspar crystals have been intensely altered to grey feldspar (very fine-grained galena impregnation) or are now pseudomorphed by aggregates of extremely fine grained muscovite and quartz. Green feldspar (plumbian orthoclase) is only preserved as rounded cores in the centre of the largest feldspar crystals. The circular remnants of green feldspar within the cores of large crystals suggest that the replacement mechanism of green feldspar with grey feldspar (galena-exsolution) was by the

diffusion of Pb and S from the margins of the grains. This observation suggests that a diffusive mechanism of replacement operated on the D1 green feldspar during D2 and or D3 metasomatism.

#### 5.5.5.2. *Syntectonic Sulphide Differentiation.*

Based on mineralogical associations observed in veins and assay data collected during in-mine exploration programmes Webster (1994a) suggested that the sulphide components of the orebodies underwent metamorphic differentiation during D2. Two mineral suites were recognised;

1. Galena, silver, gold, loellingite, scheelite, +/- chalcopyrite, tetrahedrite.
2. Sphalerite, pyrrhotite, chalcopyrite.

Sulphide differentiation of the ore resulted in silver-rich, pegmatitic galena veins filling crosscutting fracture systems within the GQH adjacent to, and within zinc-rich orebodies (eg. ALL). This relationship is observed even where the orebody is mainly composed of sphalerite and pyrrhotite. Pegmatitic galena veins are common as crosscutting features in the GQH where they overprint coarse-grained sphalerite-pyrrhotite-chalcopyrite mineralisation. They also overprint sphalerite veining within deformed rhodonite bodies in 2L and 3L (Webster, 1994a).

Fluid-phase galena mineralisation that is rich in gold and silver impregnated barren garnet sandstone units on the upper margin of 2L and adjacent to 3L in the Pasminco Mine. Lead-rich fluids were highly mobile and moved the greatest distances from major orebodies (up to 30 metres) whereas sphalerite remained close to orebodies (moving up to 15 metres) (Webster, 1994a).

#### 5.5.5.3. *Lithological Controls on Sulphide Mobilisation.*

Rock type controlled competency contrast adjacent to and within the orebodies played an important part in the structural preparation of sites for the trapping of mobilised sulphides and siliceous fluids during D2. Fracture systems, breccias and vein stockworks developed in such rock types and provided host sites for the deposition of syn-tectonically mobilised orebody sulphides. This was a particularly important influence on sulphide mobilisation within the GQH (garnet quartzite), rhodonite units

in 2L and 3L, blue quartz lode, garnet sandstone, lode pegmatite bodies, D2-garnetised rims of orebodies and some psammitic units. Such rock types remained competent at the peak of granulite grade metamorphism and deformed in a brittle manner, forming vein systems and breccias, usually in the zones of transition from F2 fold hinges to limbs. Such zones of brittle deformation seem to have formed low-pressure areas into which the contained siliceous fluids and fluid-phase sulphides could migrate. Garnet and pyroxenoids are widespread gangue constituents of the veins and breccia matrices within such zones, as well as the recrystallised vein walls.

The clastic metasediments of the MinSeq underwall have not generally provided a trap for such vein and brittle styles of mineralisation, perhaps because these rocks were too ductile during the peak of D2. No fracture systems were developed and the mobilised sulphides and siliceous fluids probably remained confined within the orebodies. The result was the extensive impregnation of competent horizons within the orebodies (e.g. the rhodonite in 3L, 2L, ALL) and the sulphide enrichment of susceptible rock types such as the banded calcite ore (2L, 1LL, 1LU), siliceous ore (3L, 1L) and silicified rocks at the orebody margins (Webster 1994a). Sulphide vein systems dominated by sphalerite also developed within some orebodies in zones of intense D2 deformation and overprinted the primary banded texture of the mineralisation (eg. 3L, BL and 2L).

The brittle behaviour of some elements of the Lode Sequence at granulite facies is probably due to one or more of the following factors:

- Mineralogy. Garnet-rich rocks, pyroxenes/pyroxenoids and unusual calc-silicate minerals were stable and competent during metamorphism, or were recrystallising at the same time as sulphides and metamorphic fluids became mobile,
- High strain rate: In some locations in fold limbs, strain was sufficient to fracture garnet-rich rocks, particularly where this occurred in concert with high fluid pressures, and
- High fluid pressure caused by the liberation of water, high CO<sub>2</sub> generation and/or the generation of a sulphide 'melt' phase. Fluid pressure and sulphide 'melts' are the probable cause of the apparent fracturing and 'mineralisation' of pegmatite adjacent to ore.



## 5.6. THIRD DEFORMATION (D3).

### 5.6.1. Introduction.

The third deformation (D3) was continuous with D2 but distinguished from it by being predominantly a shearing event, and by the formation of a lower grade and texturally distinctive mineralogy within the orebodies (Webster, 1993, 1994a).

Early retrograde (high grade) shear planes have been recognised in the Lode Sequence by:

- Abrupt changes in form surface trends that define belts of discrete foliation trends (high strain zones). Shear zones defined in this way form planar, discrete belts with a common strike that attenuate, offset or truncate F2 fold structures. Shear zones truncate other form surface trends and lithological units,
- Their association with pods and lenses of attenuated MinSeq stratigraphic units (e.g. amphibolite and Potosi type gneiss) in the Pasminco Mine,
- Sheet-like, linear, attenuated sections of the orebodies that have a consistent strike and orientation over several mine levels, and a parallel fabric in wall rocks. Such zones may truncate wall rock marker units and F2 fold structures,
- Needle-like sillimanite that forms a part of a patchily developed S3 axial plane cleavage developed in mesoscopic folds in some shear zones (especially in pelitic bands), and
- By Belts of feldspar augen bearing pelites and psammopelites, which are spatially associated with D3 shears in many areas.

D3 is characterised in the orebodies and the MinSeq by the development of a series of broad ductile belts of shearing with complex to simple internal structure. Shearing is focussed in intense shear planes at a variety of scales that traverse the orebodies and stratigraphy at acute angles. Sinistral west-block up offset along the narrow, discrete but intense shear planes offsets relatively low strain zones that lie between (such as F2 fold hinges). Offset distances in a horizontal sense are between 300 and 500 metres in the Pasminco Mine and South Mines and up to 750 metres in the British and Junction mines. The intermediate blocks usually represent preserved F2 fold hinges, or partial fold hinges. Offset has been focussed along fold limbs. Several large antiformal folds have been dismembered at an acute angle to their axial traces during shearing. At the same time, synforms have been attenuated. The most significant D3 shear planes dip

steeply (70°-85°) northwest to north and generally strike northeast-southwest (approximately 30° anticlockwise of the axial planes of F2 folds).

D3 shears have a metamorphic history that ranges from the waning stages of granulite facies metamorphism to lower amphibolite facies. Structural fabrics and mineralogical changes within ore and wall rocks are developed for all of the stages of D3. On the basis of the recognition of distinct mineralogical changes within the sheared wall rocks and the orebodies, two distinct phases of D3 shearing are recognised, (e.g. Webster 1994a):

- D3A: a high grade phase (upper amphibolite to granulite grade mineralogy) and
- D3B: lower grade phase of shearing characterised by quartz-muscovite-biotite shearing (comparable to the G2A and G2B events defined by Webster, 1994a). D3B shears are the well-documented retrograde shears that have been described by previous workers (eg. Vernon and Ransom, 1969; Laing et al., 1978).

The characteristics of D3A and D3B are summarised in Figures 5.23 & 5.24.

#### 5.6.1.1. *D3A shears.*

There is a transition from D2 to D3A shear zones in some cases and many D3A structures were initiated during the early retrograde stages of high-grade regional metamorphism. Shears that formed in the waning stages of D2 were continuously active into early D3. D3 shears persisted throughout the Olarian retrograde metamorphism, changing character as the prevailing temperature and pressure diminished. Early retrograde ductile shears are often associated with localised F3 folds (Figure 5.25 and Figure 4.13). The D3A structures were the focus of all the shearing which has affected the mining field and were very long-lived. They formed in the waning stages of granulite facies metamorphism and persisted through to lower amphibolite grade (D3B). D3 shears can therefore preserve a sequential series of shear fabrics, with the earlier (D3A) structures often being obliterated by later D3B and possibly D4 features (Webster, 1994a).

D3A structures developed in the mines area have a strike of approximately 035-045° and dip steeply to the north-northwest. D3A shearing produced transposition of the

## Summary of the features of D3A (OLARIAN OROGENY)

Formation of BOA Shear System & the Thomson Shear.	D3A Effects on F2 Folds	Associated Styles of Mineralisation & Alteration	D3A Structures & Fabrics.
<p>250-300m sinistral movement, northwest block up (reversed). Intersect F2 fold axes at approximately 20° to 35° to their strike.</p> <ul style="list-style-type: none"> <li>Channel Shear, Central Mine Shear,</li> <li>Main Shear, Western Zone of Shearing in Pasmunco Mine.</li> <li>Development of the B Lode Shear &amp; related structures near hinge of ZCA.</li> <li>Staurolite zone on upper limb of ALL &amp; within distal B Lode ('CL').</li> <li>250m sinistral NNE trending, west block up displacement of 3L &amp; 2L in the Browne Shaft area (Thomson Shear).</li> </ul>	<ul style="list-style-type: none"> <li>F2 folds geometries are accentuated by shearing along southern &amp; northern margins of 2L (&amp; to a lesser extent 3L) to produce the 'limbs' of the orebody. Final geometries of the ZCA, NBHCS, SMA, CMA established.</li> <li>Dissection of the BHP Synform &amp; shearing in the north and south limbs of the Block 14 Antiform. Central Mine Synform attenuated &amp; mostly destroyed</li> <li>Dislocation and dismemberment of 2L throughout the Central &amp; British-Junction regions of the mining field.</li> <li>Dissection &amp; dislocation of the hinge of the ZC Antiform. GQH dissected in 'rollover' position 'CL' offset from BL by 250m movement of B Lode Shear.</li> <li>The main part of the final geometry of the Western Keel Synform established in 2L. Offset of hinge of WKS in ALL from that in 2L</li> <li>Structural dislocation of the keel of Southern Cross Synform by 'Prograde' Main Shear.</li> </ul> <p>Intense D3A transposition in the northeastern region is closely associated with complex isoclinal folding &amp; the distinction between F2 folding &amp; D3A shearing is much less obvious than in the southwest.</p> <ul style="list-style-type: none"> <li>Dislocation of competent infolded garnet quartzite blocks within the keel of the NBHCS, associated with sulphide mobilisation &amp; silicification. Also well developed adjacent to the ZCA (commenced in D2?)</li> <li>Development of the 'droppers' in association with Main Shear adjacent to 2L &amp; 3L in the Pasmunco Mine &amp; in the South Mine</li> <li>Extreme attenuation of 3L segments in lower mine levels focussed mainly in the Central Mine Antiform</li> <li>Attenuation of F2 folded geometry of 2L &amp; 3L between 29 &amp; 32 Levels in the North Mine</li> <li>Shear offset of 3L &amp; 2L between 32-34 Levels of North Mine (Fitzpatrick Orebody)</li> </ul>	<ul style="list-style-type: none"> <li>Bustamite, wollastonite, hedenbergite crystallisation within calcic mineralisation in sheared sections of 2L.</li> <li>Continued development of breccias &amp; stockworks within the garnet quartzite, &amp; zones of saccharoidal silicification within sheared parts of the orebodies, started during D2. Continued development of the metasomatic, siliceous alteration of clastic metasedimentary wall rocks initiated during D2, which probably reached a culmination during D3A. Forms siliceous styles of low grade mineralisation adjacent to ore lenses in shear zones.</li> <li>Silicification &amp; alteration of lode pegmatite, especially southwest of the GQH.</li> <li>Intense silicification of thinned peripheries of the orebodies at contacts with clastic metasediments, especially 1LL (e.g. 20 Level sill, Pasmunco Mine) &amp; S1L.</li> <li>Early phases of the development of irregular patches of fibrous and acicular cummingtonite within some fractures on orebody margins and as patches of skeletal crystals within the matrix of saccharoidal siliceous sulphide ore. Also developed in association with saccharoidal quartz, in strongly attenuated parts of B Lode on the 16 &amp; 17 Levels of the Southern Cross area of the Pasmunco Mine. See D3B.</li> <li>Well formed garnets (gem) within siliceous, galena-rich veining within ore horizons (e.g. A Lode lower on the 17 Level).</li> <li>Development of 'Axial Plane Orebodies' in B Lode Shear. Staurolite formation.</li> </ul>	<p>Complex isoclinal F3 folds develop in shear zones, especially where shear planes merge.</p> <ul style="list-style-type: none"> <li>S3 sillimanite is characteristically needle-like in habit and parallel to F3 axes.</li> <li>An S3 biotite-defined schistosity is developed in clastic metasediments of the northern leases &amp; is characterised by the re-orientation of S1 fibrolite to form the 'flame shaped' &amp; ragged S1/S3 fibrolite bundles.</li> </ul>

**Figure 5.23.** Summary of the features of the early retrograde (D3A) deformation in the Broken Hill mineralised system & Mine Sequence.

## Summary of the features of D3B (OLARIAN OROGENY)

Quartz-Muscovite-Biotite Shear Zones	D3B Effects on Earlier Structural Features.	Associated Styles of Mineralisation & Alteration	D3B Structures & Fabrics
<p>D3B shears seem to have two distinct phases:</p> <ul style="list-style-type: none"> <li>• <i>Early biotite-rich phase</i></li> <li>• <i>Later muscovite-rich phase</i></li> </ul> <p>They tend to be focussed along major stratigraphic contacts, particularly the contacts of the Garnet Quartzite Horizon in the southwest part of the mining field.</p> <p>The main development of D3B shearing is in the north-eastern part of the mining field.</p> <p>Important D3B shears are:</p> <ul style="list-style-type: none"> <li>• 'retrograde' Main Shear (NBHC &amp; SX),</li> <li>• Termination Schist Shear &amp; early phases of the Central Fault.</li> <li>• Major phase of development of the:</li> <li>• Globe-Vauxhall &amp; Western Shear System &amp; associated structures.</li> <li>• DeBavay Shear,</li> <li>• later phases of Potosi Shear?</li> <li>• Early phase (quartz-muscovite-biotite schist) of Lords Hill Fault.</li> <li>• Final stages of B Lode Shear development (fracturing of clasts &amp; actinolite formation?)</li> <li>• Retrograde (later) part of the Dropper &amp; B Lode Shears</li> </ul>	<p>Extensive development of quartz-muscovite-biotite shear zones within the D3A subordinate planes of the BOA.</p> <p>Retrograde quartz-muscovite-biotite schist zones developed in the planes of the D3A Thomson Shear.</p> <p>Modification of the D2-D3A geometry of 3L &amp; 2L in the North Mine, between the 26 &amp; 29 Levels &amp; completion of the attenuation of 2L &amp; 3L between the 29 &amp; the 32 Levels of North Mine</p> <p>Completion of shear offset of Fitzpatrick Orebody components of 2L &amp; 3L from the main orebodies by the Globe-Vauxhall Shear in North Mine.</p> <p>Dislocation of the Fitzpatrick Orebody &amp; "2K" Mineralisation (northeastern continuation of 2L &amp; 3L) by the Western Shear.</p> <p>Structural dislocation of Centenary Mineralisation from the Western Mineralisation by Globe Vauxhall Shear Zone (Haydon &amp; McConachy, 1987)</p>	<p>Later elements of the dropper shears hosting mineralisation, including quartz-muscovite-biotite shear fabrics on dropper ore contacts &amp; within the D3A shear fabric of the dropper wall rocks.</p> <p>Actinolite in fractures in quartz veining &amp; wall rocks (in D3A zones with dropper mineralisation)</p> <p>Amphibole filled fractures in -bearing quartz veins, Cumingtonite in deformed quartz veins &amp; infiltrating ore; particularly in mineralisation associated with garnet quartzite that has been overprinted by silicification.</p> <p>Muscovite alteration of pegmatite dykes and other wall rocks.</p>	<p>Quartz-muscovite-biotite schist belts from centimetre to hundreds of metres in width.</p> <p>Extensive development of quartz-muscovite-biotite shears &amp; retrograde schistosity on major lithological contacts (particularly competent units like garnet quartzite, psammite &amp; quartzofeldspathic units).</p> <p>Pervasive retrogression of all S1(fibrolite bundles) /S2/S3 sillimanite throughout pelite in much of the northeastern part of the mining field, including the North Mine.</p> <p>Pervasive muscovite-biotitic foliation throughout attenuated areas of the Pasminco Mine (particularly the ZC area)</p> <p>Needle-like sillimanite in early phases?</p> <p>Quartz-muscovite-biotite margins &amp; actinolite growth within clear quartz veining on margins of earlier D3A droppers.</p> <p>Pervasive Retrogression in later phases (sericitised)</p>

*Lower amphibolite-greenschist grade*

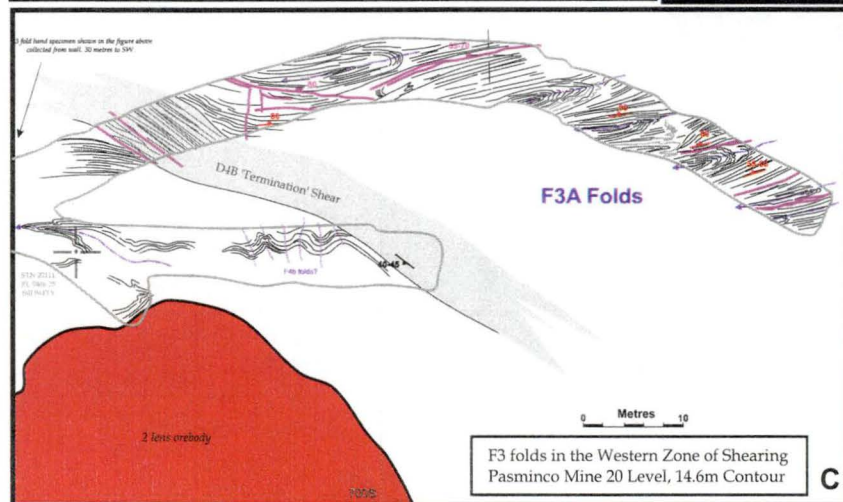
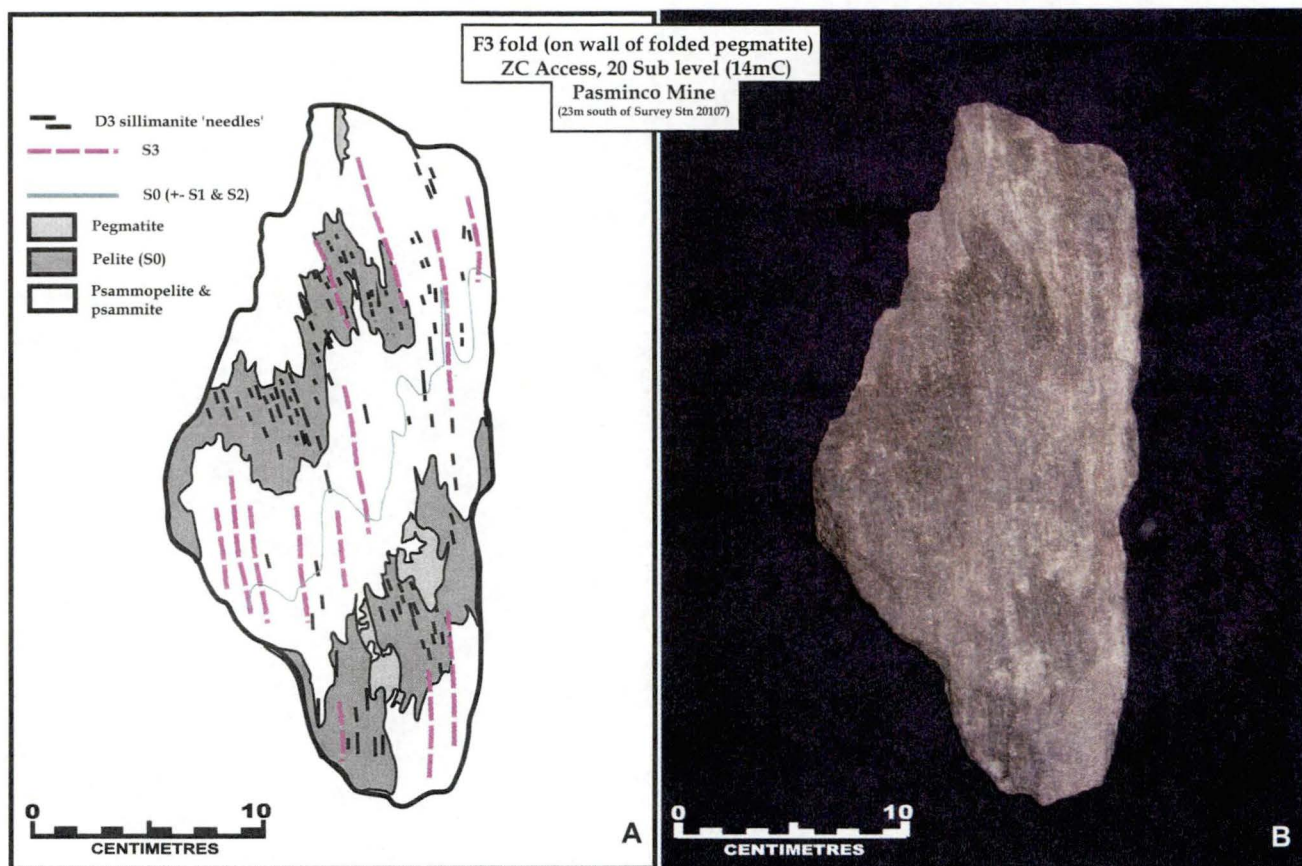
**Figure 5.24.** Summary of the features of the second phase of the third deformation (D3B) within the Broken Hill mineralised system & Mine Sequence.

pre-existing structural and stratigraphic elements of 2L and 3L by rotation into intense sinistral shear zones and dislocated the folded geometry of the GQH. D3A shears exhibit horizontal movement in the order of 300 to 750 metres. Offsets of stratigraphic marker units and the attenuated, dissected and dislocated F2 folds show that D3A structures have a dominant sinistral, west-block up sense of movement. D3A shear zones may rotate, attenuate and dislocate the folded geometry of the MinSeq. However, these structures only rarely produce truncations of the stratigraphy.

Three D3A shear systems transect the BH deposit at approximately 20 degrees to its D2 strike. The two most significant are known as the BOA Shear System and the Thomson Shear Zone (van der Heyden and Edgecombe, 1990).

1. The BOA Shear System (section 5.6.2) extends from the northeastern part of the Pasminco Mine to the BHP & Block 14 Mines (Gustafson, 1939, Gustafson et al., 1950; Webster, 1993 & 1994a). It is focussed along the southeastern margin of the orebodies in the Pasminco, South and Central mines, with significant splays transecting the MinSeq, particularly within the GQH. The BOA persists north-eastwards through the BHP and Block 14 mines and diminishes in strength to the north of the orebodies in the British Mine area. The BOA system passes away from the orebodies in the southwestern part of the Pasminco Mine, having only relatively minor effects in the footwall of B Lode, but causing considerable thinning and dislocation of the Southern Cross Synform.
2. The Thompson Shear Zone (van der Heyden and Edgecombe 1990) (section 5.6.7) transects the deposit between the Blackwoods and Browne Shafts, in the British-Junction Region of the field (ML's 16 and 39). It is focussed along the southern margin of 3L for much of its southwestern extent, but transects the orebodies in the Menindee Rd area. The Northeastern Region of the mining field lies to the northeast of the structure. Dislocation of the main orebodies is more marked in the area affected by the Thomson Shear than it is in the regions transected by the BOA Shear System.

A third zone of D3A shearing is now represented by a high-grade phase of movement on the Globe-Vauxhall Shear System. This early shear zone caused the attenuation of 2L and 3L below the 27 Level of the North Mine, and the dislocation of these orebodies between the 30 and 36 Levels (see section 5.6.7.4).



#### F3A fold styles in the Southern and Central Regions of the Broken Hill Mining Field

**Figure 5.25.** Styles of F3 folds developed within D3A shear zones adjacent to the main orebodies in the southwestern and central regions of the mining field. The style of F3 folds within D3A shear zones is consistent throughout the southwestern part of the mining field.

**a & b.** Photograph of hand specimen and sketch of the same specimen showing details of the an F3 fold of the type that is commonly seen in the southwestern region, adjacent to 2L ZC Access, 20 Sub level (14mC) Pasminco Mine (23m south of Survey Station 20107).

**c.** Backs mapping showing F3 folds in the Western Zone of Shearing, Pasminco Mine 20 Level, 14.6m Contour. The 2L orebody is shown in red.

**d.** Interpreted from surface map and geological plan, based on the mapping of Gustafson (1939) and showing F3 Folds associated with the Belt of Attenuation. BHP Mine 4 Level, 64' Contour.

See also Figure 4.13, which shows a body of garnet sandstone tightly folded by multiple F3 (?) folds within the Western Zone of Shearing.





D3A was associated with a series of characteristic styles of mineralisation, including saccharoidal quartz and calc-silicate pyroxenes and pyroxenoids (Webster, 1993, 1994a), which have clear overprinting relationships with many of the mobilised (D2) and all of the stratiform (S0) styles of mineralisation.

Where D3A shears developed parallel to the post-D2 strike of the 2L and 3L, such as in the Pasminco Mine and South Mine areas, shearing was focussed along ore-metasediment contacts and the strike was influenced by the F2 fold orientation. In the ZC area, 2L and 3L lay completely within the influence of the BOA and its subordinate structures. F2 folds were transposed and rotated into parallelism with the BOA (Webster, 1993, 1994a). In the South Mine area, F2 folds within 2L and 3L were particularly affected by D3A and were severely transposed and structurally thinned along the eastern margin of the deposit. Fold keels in 2L and 3L were drawn out into strongly tabular bands of mineralisation along the eastern margin of the deposit while F2 hinges to the west of the structure (generally antiforms) were well preserved. Where the angle of incidence between the strike of the orebodies and D3A shearing was greater, such as in the Thompson-Browne Shaft Region (the Thompson Shear), a 300-750 metre sinistral offset of the entire mineralised sequence resulted. The current geometry of the NBHCS, ZCA, WKS, SXA, SXS and folding throughout the South Mine area is due to a combination of F2 folding and D3A attenuation.

D3A structures developed in the Pasminco Mine are developed parallel or sub-parallel to the stratigraphy and can be difficult to recognise in drill core, underground exposures and outcrop because bedding has been rotated into parallelism with the shear boundaries and is difficult to distinguish from undeformed bedding (Webster 1994a). However, silicification of the mineralisation and wall rocks is a characteristic of D3A shears and allows them to be distinguished (eg. the prograde Main Shear on the eastern limb of 2L at NBHC). Such silicification of mineralisation and wall rocks within shear zones results in distinctively saccharoidal-textured rocks (Webster, 1993, 1994a). D3A shear zones may also be distinguished in underground exposures and outcrop by low angle bedding truncations, lenticularity of competent layers (especially psammite bands), limbless folds and offsets or sudden changes in strike of stratigraphic marker units; including 2L and 3L (Webster, 1994a).

To the north-west and south-east of the mining field, D3A shears propagate along lithological contacts and layering, such as the contacts between granite gneiss and



metasediments, Potosi type gneiss units, amphibolites and pelitic units (in fact any part of the sequence where there is a significant ductility contrast). The interaction between D2/D3A structural and primary stratigraphic control produces an anastomosing array of D3A Belts of Attenuation that merge in stratigraphy-parallel zones to the east and west of the mining field (Webster, 1994a).

D3A shearing was associated with extensive siliceous metasomatism of orebody margins in attenuated zones and planar mechanical mobilisation of ore within shear planes (Droppers).

#### 5.6.1.2. *D3B shears.*

The later stages of D3 are marked by the development of large and often laterally persistent retrograde quartz-muscovite-biotite schist zones throughout the mining field and district. D3B shears now represent the most obvious and readily recognisable shear zones within the Mine Sequence. They show a mineralogical diversity, ranging from biotite-quartz-sillimanite schists to quartz-muscovite-biotite dominated types. In several localities in the Pasminco Mine, there is a sharp definition between an apparently earlier biotite dominated D3A fabric and an overprinting muscovite-biotite dominated schistosity (Webster 1993; 1994a).

Narrow quartz-muscovite-biotite shear zones developed on the margins of D3A structures but also frequently developed outside such zones. They tend to be more transgressive of stratigraphy, in some cases causing significant offset of the MinSeq and orebodies. D3B shears were also reactivated to form puggy, chloritic faults during D4.

Important examples of D3B shear zones are:

- Globe-Vauxhall-Western Shear System,
- The DeBavay Shear,
- The quartz-muscovite-biotite shear fabric of the early Lords Hill 'Fault' (reactivated during D4A),
- The 'retrograde' Main Shear (Pasminco Mine),
- Central Shear (in metasediments below 2L in the Pasminco Mine), and the
- Termination Schist Shear (Pasminco Mine)

The distribution of the most significant D3B shears in the mines area is shown in Figure 5.14 (contained in separate map folder).

### 5.6.2 The BOA Shear System.

The largest and best-defined D3A shear zone occurs within the southwestern half of the mining field and is referred to in this thesis as the BOA Shear System<sup>1</sup> (BOA). The BOA extends from the area of the Delprats Shaft, to the Southern Cross area and is a tightly defined, tabular zone of ductile attenuation, transposition and folding with a vertical to steep westerly dip. In the South Mine area the BOA consists of a tabular zone of intense transposition approximately 40-50 metres wide that is focussed along asymmetric second order F2 synformal keels along the eastern margins of 2L and 3L and shows a strong west block up sinistral sense of movement. F2 antiforms to the west of the BOA are mostly unaffected.

The BOA was defined by Gustafson (1939) as follows,

*"The tightest folding and greatest stretching of the ore-bearing formations anywhere within the complex anticlinal region is obviously confined to a narrow belt about 150 feet wide which coincides in a general way with the crease that is the Eastern Syncline. Actually the belt extends chiefly along the east side of the Western Anticline and frequently, but not invariably, includes the Eastern Syncline. At the north end of the field, where the Eastern Syncline has lost its significance, the belt occupies the west limb of the Eastern Anticline. The belt has no clearly defined limits but almost any cross-section of the lodes reveals that the westernmost minor folds are fairly open whereas the minor folds near the footwall of the lodes are tight and often greatly elongated. This belt of most intense plastic deformation is of supreme importance. The Broken Hill orebodies were localized where this structure intersected the favourable beds of No. 2 Lens and No. 3 Lens ore formations. Whatever minor folds happen to be involved in this belt are greatly attenuated although the same minor folds elsewhere may be very open."*

The term "Belt of Attenuation" is abandoned for the purposes of this study because Gustafson's original 1939 definition implies that the entire belt of rocks hosting the orebodies is highly strained and that high grade shear zones are just the planes of most intense shearing within the whole belt. This is not the case and the majority of the MinSeq is only weakly strained within the 'belt' that Gustafson defines. Intense ductile shearing is confined to narrow discrete planes. The rocks in between (mainly fold hinges) are relatively unstrained. Therefore, the name BOA Shear System is adopted that recognises the long precedence of Gustafson's (1939) naming and definition but allows for the different interpretation of the structure derived from the current study. The BOA Shear System is an anastomosing array of shears, rather than

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<sup>1</sup> Note: The term "shear system" is used in this thesis to denote a cluster of distinct but related shear zones, which may merge along-strike, up or down dip but which offset large masses of relatively unstrained rock between.

a continuous belt of attenuation. Significant individual shear planes within the BOA are named separately.

From the distortion that D3A shearing produces in the axial surfaces of F2 folds such as the ZCA, NBHCS and WKS (and folded stratigraphic markers in the orebody), movement direction of the BOA is west block up (reverse) and sinistral. The subordinate planes of the BOA such as the WZS and MS also exhibit west block up, sinistral movement as shown by strongly drawn out and boudinaged mesoscopic F2 fold hinges in these areas (Webster, 1994a). The movement indicators cited above give a sinistral sense of movement for the entire BOA. Microstructural movement sense indicators from the western side of 2L agree with the sinistral sense of movement interpreted here (E. Rothery pers comm., 1993) and the same sense of movement has been interpreted for the western side of 2L at ZC using the offset of stratigraphic markers within the metasediments (Stockfeld, 1993b).

The BOA is confined to the southeastern margin of 2L and 3L throughout the South Mine area but divides into a series of subordinate structures in the BHP, Central, South and Pasminco mines. The BOA is focussed along the southeastern margin of the orebodies in the Pasminco, South and Central mines, with significant splays transecting the MinSeq, particularly within the GQH. The BOA persists north-eastwards through the BHP and Block 14 mines and diminishes in strength to the north of the orebodies in the British Mine area. The BOA system passes away from the orebodies in the southwestern part of the Pasminco Mine, having only relatively minor effects in the footwall of B Lode.

The BOA shear system is an array of narrow (2 to 20 metre wide), northeast-southwest striking, anastomosing planes of intense shearing that intersect the orebodies at an acute angle (approximately 30°) and which 'wrap' around large masses of ore within preserved fold hinges (low strain zones) (e.g. Figures 5.11 & 4.20). Splays branch across the orebodies, focussed in locations between major fold hinges or clusters of fold hinges and attenuate or offset the ore zones. In general, the BOA system passes from the Southern Cross Shaft area of the Pasminco mine, (southwestern end of the field) to the northern side of the orebodies in the north central (BHP-Block 14 Mine) part of the field.

Low strain zones comprising earlier (F2) fold hinges (containing large masses of ore) occur between the shears and are rotated to varying degrees. Rotation of low strain zones produces changes in fold plunge across shears. Fold plunge within the discrete zones are internally consistent but differ in orientation from adjacent zones to the northeast and southwest. There was a rotational component in the movement along the shear planes of the BOA.

The BOA shear system extends along the southern side (eastern side in mine grid terms) of the orebodies eventually passing across to the northern (mine grid western) side of the zone in the Junction-North Mine area. Gustafson (1939) and Gustafson et al., 1950 & 1952) had a good understanding of the nature of the BOA, which they defined and named. They also had a good understanding of the nature of the intense shear planes within the zone, which they referred to as the "Main Shear". However, they failed to recognise that between the narrow planes of intense shearing, there were zones of much lower strain, mostly occupied by F2 fold hinges and the orebodies. The fold hinges are un-sheared (possibly definable as boudins).

Kenny (1928; 1929) understood something of the nature of the BOA system and was the first to recognise the transgressive nature of shears within the orebodies when he defined the trace of his "Main Ore Channel" (referred to here as the Channel Shear) in the orebodies.

#### 5.6.2.1. *Planes of the BOA Shear System.*

The planes of intense D3A shearing in the South, Central and BHP mines host shear bounded and attenuated sheets of high grade ore. The sheets are remarkably continuous with thickenings and bulges that represent remnants of F2 fold hinges. Such sheets of ore cross cut the MinSeq stratigraphy and project well into the footwall sequence, reaching almost to the thin Consols Amphibolites (e.g. 970 Level South Mine). The sheets of ore provided the main ore sources at depth in the South and Central Mines and 'pinched off' isolated or semi-isolated lenses of ore were mined on the lowest levels (e.g. Figure 5.11, 5.20 & see maps BHP5, NBH11 & NBH12 in Appendix 1).

In the central part of the mining field the most important shear planes identified are the (high grade) Main Shear, Central Mine Shear, Channel Shear and Block 14 Shear.

In the Pasminco Mine, the most important subordinate structures are known as (from south to north), the (high grade) Main Shear, the Western Zone of Shearing and the B Lode Shear (Webster, 1994a).

- The High Grade Main Shear (northeastern Pasminco Mine),
- The Western Zone of Shearing (NBHC),
- The B Lode Shear,
- The ALL Dropper Shear,
- The Western Dropper and the
- The 2L Dropper

**Main Shear:** The Main Shear (MS) was defined by Gustafson et al., (1952) as consisting of several *en echelon* planes of shearing within the BOA. This definition is abandoned here and is only retained for that plane of high grade shearing that extends along the southern margins of the orebodies from the South Mine area into the Pasminco Mine (NBHC) area. This definition reflects the 1997 use of the term by the Geology Department of the Pasminco Mine. The MS bifurcates in the South and Central mines and the northern branch cross orebody to become Central Mine Shear. The Central Mine Shear and the Main Shear rejoin at depth below the main mass of 3L in the Central Mine Synform.

Around the 20 Level of the ZC area of the Pasminco Mine (20 Level cut and fill stopes), large masses of attenuated calcitic 2L ore within the MS are massively re-crystallised to form an apparently disordered (they may be oriented) zone of well-formed, very coarse-grained bustamite crystals. D3A bustamite forms clustered masses of crystals, and coarse, well-formed but matrix separated crystals ranging up to 25cm, hosted within calcite and sulphides (Figure 5.9h).

**Central Mine Shear.** (BHP-Central Mine to South Mine area). Recognised as one of the planes of intense shearing within the BOA by Gustafson (1939) and referred to as the Main Shear. The Central Mine Shear (CMS) produces intense attenuation of 2L and 3L along the southeastern side of the orebodies in the Central Mine.

**Channel Shear.** (BHP to Block 14 mines). This shear was recognised as the “Main Ore Channel” by Kenny (1928; 1929; 1932) and is the structure that dislocates and offsets

the hinge of the BHP Synform in the BHP Mine. The north block up sinistral offset produced by this shear is approximately 150 metres.

**Block 14 Shear** (Block 14 Mine, southern side of orebody). The Block 14 Shear is a splay structure that produced significant attenuation of the southeastern side of 3L in the Block 14 Mine and may represent a ramp between the BOA System and the Thompson Shear Zone.

**Western Zone of Shearing**. (Pasminco Mine). The WZS is developed in a belt of metasediments between the hangingwall of 2L and the footwall of the GQH that hosts ALL(WAL) in the northeastern Pasminco Mine. It persists in this position to the southwest, to where it lies on the footwall (southeastern) side of B Lode and the GQH in the Southern Cross Shaft area of the Pasminco Mine. In the latter region, it is known as the Main Shear. The WZS produces the dislocation of the Southern Cross Synform and Southern 1 Lens in this area (see section 5.6.3).

**B Lode Shear**. (Pasminco Mine). The B Lode Shear persists throughout most of the Pasminco Mine, from the 12 to the 17 levels (e.g. Figure 4.15b & see maps NBH12 to NBH17 in Appendix 1) and is one of the shear planes of the BOA System that cause significant effects in the GQH. The shear initiates in the common limb areas of the ZCA and the NBHCS and projects southwest, to the northwest of BL. It offsets the northeastern continuation of the BLH approximately 300 metres to the southwest, relative to the main mines area and is strongly mineralised (see section 5.6.4).

**D3A Globe-Vauxhall Shear**. (occurs at depth in North Mine). The attenuated shape of 3L and 2L in the lower levels of North Mine is evident above the first significant development of the quartz-muscovite-biotite shear fabric of the D3B Globe-Vauxhall Shear. The attenuation of the orebody is severe and F2 fold geometries and the S2 fabric defined by lead grade distribution are 'flattened'. The evidence suggests that shearing during D3A has produced the attenuation and at least some of the offset of 2L and 3L between the 30 Level and the Fitzpatrick area of North Mine (see section 5.6.7.4).

#### 5.6.2.2. *BOA in the Pasminco Mine.*

The BOA system reaches a maximum width of 150 metres in the Pasminco Mine where it undergoes a significant change in nature that is coincident with the development of significant garnet quartzite in the Lode Sequence. The BOA becomes a more complex structure composed of several discrete subordinate planes, which propagate along the margins of thickened elements of the GQH located within F2 fold hinges. The contacts of 2L were also a major locus of subordinate planes of D3A shearing (Webster, 1994a).

A Lode Lower, 1LU, 1LL, 2L and 3L lying within or adjacent to the tightly infolded part of the GQH in the keel of the NBHCS lie within the influence of the BOA forming a low strain zone between two major planes of the system; the Man Shear along the southern margin and the WZS on the northern margin. Several zones of weakly affected metasediments that preserve F2 folds lie between the strongly attenuated eastern and western margins of the orebodies (Webster 1994a). The Southern Cross area lies mainly to the west of the BOA and suffers little D3A attenuation. BL, S1L and SAL are only moderately affected by minor subordinate planes of the BOA, including the B Lode Shear, WZS and some minor D3A shearing on the western contact of the GQH.

The BOA produces a pervasive distortion of all the pre-existing structural and stratigraphic features of 2L and 3L, warping the F2 folds in even the least attenuated regions of the orebody. Within the boundaries of this structure, large-scale transposition of all lithologies has occurred while maintaining stratigraphic integrity. This feature results in whole sections of the MinSeq being re-orientated to lie parallel with the boundaries of the BOA but showing no mesoscopic scale signs of the transposition (Webster 1994a). The post-D2 geometry of the GQH and 2L provided a strong influence on the sites in which subordinate planes of the BOA developed.

To the south, in the NBHC area of the Pasminco Mine a large proportion of 2L and the GQH lie between the subordinate planes of the BOA and are relatively unaffected by D3A shearing. Some D3A shearing is focussed along the eastern and western margins of 2L at NBHC, taking the form of two distinct and localised subordinate zones of shearing known as the WZS and the Main Shear (MS). F2 folds are preserved within the core of 2L between the WZS and the MS in this area. In the northern part of the



Pasminco Mine the effects of the BOA are pervasive; F2 folds are completely re-orientated and attenuated and the distinction between the WZS and PMS diminishes.

Widespread silicification of ore and wall rocks within attenuated zones took place around the margins of 2L during D3A. The development of both sulphide-bearing and barren quartz veining was widespread at the orebody contacts and within the adjacent wall rocks (Webster 1993, 1994a).

### **5.6.3. The Western Zone of Shearing.**

The Western Zone of Shearing was first identified by Webster (1994a) and named the Western Zone of Transposition and Folding. This cumbersome name is abandoned in favour of the shorter title: Western Zone of Shearing (WZS). It should not be confused with the D3B 'Western Shear'; an important structure affecting the North Mine area.

The WZS consists of a tightly constrained, lithologically controlled belt of D3A attenuation which exploits a series of pre-existing, planar lithological features of which the most important are the contacts of the GQH and the contacts (and thinned areas) of sulphide-silicate-carbonate mineralisation (especially 2L). While the shear zone is continuous, the actual subordinate planes of most intense dislocation are not necessarily joined, but tend to focus on lithological contacts (e.g. maps NBH18 to NBH21 in Appendix 1). Lithological continuity is often maintained across the plane of the zone and it is only in exceptional locations (such as in the tightly attenuated hinge of the ZCA) where dislocation can be recognised. As is seen in many of the D3A shear zones in the southwestern mining field, the WZS has localised occurrences of mesoscopic F3 folds with axial planar sillimanite 'needles' developed in pelitic layers (e.g. Figure 5.25, see also Figure 4.13). See below.

On the 13-20 levels of the Pasminco Mine, the WZS is located on the western side of the orebody, mainly confined to a belt of psammites, psammopelites and pelites between 2L and the GQH hosting the western limb of ALL. Subordinate planes of most intense attenuation are confined to the western contact of 2L and the contact of garnet quartzite in this region of the mine stratigraphy. The WZS projects southwards and down plunge from the upper levels to merge with the Main Shear. It then propagates along the southern margin of ALL and the GQH on the 16 and 17 Levels of the Southern Cross Shaft (see maps NBH18 to NBH21 in Appendix 1).

Within the GQH, the WZS and its subordinate planes produce a series of features that include:

1. Belts of feldspar augen bearing pelite between ALL ('Western A Lode') and 2L (especially on the footwall of the Garnet Quartzite Horizon hosting ALL).
2. The "Axial Plane Orebodies" (Stockfeld, 1993a & 1993d).
3. Staurolite zone on the upper western limb of ALL (Stockfeld, 1993d).
4. Vertical D3A banding within garnet quartzite in the 'rollover' position in ALL.
5. The barren upper western limb of ALL.
6. The staurolite zone in 'CL' which was identified by J. Stockfeld (pers comm, 1993), and interpreted by him to be a retrograde feature, probably represents a plane of D3A attenuation related to the position where the WZS projects upward through the BL position.
7. The sinistral, west block up dislocation of the western limb of ALL (Western A Lode) from the main orebody in the hinge area of the ZCA and within the NBHCS .
8. The dislocation of 'C Lode' from B Lode, giving it the appearance of a separate mineralised horizon.
9. A plane of shearing that has exploited the up-dip 'limb' of BL in some areas (A Wilson pers comm. 1994).

#### 5.6.4. D3 Shear-hosted Orebodies.

There is a close spatial relationship between D3A shears and the transgressive, shear hosted and structurally mobilised bodies of mineralisation known by Pasminco geologists as "Droppers" and "Axial Plane Orebodies" (Stockfeld 1993a & 1993d). These structures contain recrystallised 'saccharoidal' mineralisation and associated wall rock silicification (Webster, 1994a). The most important such structures include;

- The B Lode Shear & the Axial Plane Orebodies of B Lode (Figure 4.15b),
- The Western Dropper (Figure 4.9a) and smaller 'droppers' in the Main Shear (Figure 5.7) in the Pasminco Mine,
- Elements of ALL where sulphides have been syntectonically mobilised in the keel of the NBHCS.

- Shear hosted attenuated ore within the Thompson Shear in the British Mine (Figure 5.12),
- The shear hosted attenuated sheets of 3L ore in the Main, Central and Channel shears in the Central, South and BHP mines are transgressive of the MinSeq stratigraphy (Figure 5.11 & 5.20),
- Elements of 2L and 3L between the 26 and 30 levels of the North Mine (?) (e.g. see Figure 5.26 in separate map folder, and see maps NTH26 to NTH36 in Appendix 1), and
- Possibly the Fitzpatrick Zinc Lode (D. Larsen pers comm, 1995, though this seems more likely to be a dislocated segment of the main orebodies, or 4.5 mineralisation) (see map NTH36 in Appendix 1)

Stockfeld (1993a) has identified structurally controlled “Axial Plane Orebodies” (APO), which occur along the northern side of the ZCA where the hinge is weakly developed. He interpreted them to be piercement structures that were mobilised along axial planar cleavage during sulphide mobilisation into the antiformal hinge. However, the APO's are here attributed to the B Lode Shear, a plane of attenuation and shearing which passes through the BL-'CL' positions. These orebodies were produced by elements of the B Lode Shear where it projects upwards, skimming past BL and its associated garnet quartzite in the position where it lies near the hinge of the ZCA. This structure produces the offset between BL and the 'CL' position to the west. The sinistral, west block up movement sense of the B Lode Shear is interpreted to be responsible for the formation of this mobilised type of orebody.

Actinolite was identified in the APO's by Stockfeld (1993d), a feature that is interpreted to represent late stage (D3B) movement along the B Lode Shear (see section 5.6.8.1).

#### **5.6.5. Relationship of A Lode to Western A Lode Mineralisation.**

The mineralisation known as Western A Lode is continuous with that in ALL, however due to the effects of the sinistral, west block up movement of the WZS and the B Lode Shear and their related structures, there is a structural break between the two areas. A degree of ductile attenuation has taken place within the zone of dislocation and the WZS consists of a number of lithologically controlled sub-planes of intense shearing. A degree of lithological connection has been maintained across the discontinuity (e.g. see map NBH16 in Appendix 1).

The F2 fold geometries (WKS, ZCA and NBHCS) in ALL have been significantly modified by the D3A attenuation, mostly associated with the WZS, where it interacts with the folded geometry of the GQH contact (especially where it is folded around the hinge of the ZCA). The hinge area (or rollover position) of ALL is truncated and offset to the south relative to Western A Lode along the plane of the WZS. The position of the WZS within the ALL-WAL area is dictated by the folded contacts of the GQH.

Important sub-planes of the WZS have caused intense deformation throughout ALL and A Lode Upper. Shear planes have propagated along the footwall contact of the GQH in the WAL region and along the western margin of the GQH, where it is folded into the NBHC Synform. Shearing is intense in the position where the garnet quartzite zone associated with 1LU and 1LL pinches out adjacent to the ZCA hinge position, and shearing also hosts the elongated band of 2L within the core of the ZCA between the 15-17 levels.

The ALL "rollover" position in the hinge of the ZCA (which was stoped as the "Rollover" stope) is actually the position where the main mass of ALL mineralisation crosses the hinge position of the ZCA. This area is not an enrichment of the fold hinge by mobilised sulphides preferentially being enriched within a fold hinge position.

The geometry of the northern limb of the WKS within the GQH hosting 'Western A Lode' has been modified by mesoscopic F3 folds (e.g. maps NBH18 & NBH20 in Appendix 1)

#### **5.6.6. Augen Feldspar Pelites.**

A belt of augen feldspar pelite has been mapped by the writer between the western limb of ALL and 2L on the 19 and 16 Levels. A similar zone recorded by Hudson (1994) in the immediate footwall of the western limb of ALL and the GQH on the 13 Level may represent one of the manifestations of the plane of the D3A WZS.

Augen feldspar pelite consists of lensoidal, translucent grey feldspar augen that range in size up to 1cm and a well-developed schistosity defined by white fibrolite & biotite with medium & fine-grained garnets. The rock has a moderate to strong S-C fabric ('fishscale' texture). Finer grained, more psammitic layers have only a weakly

developed foliation. In some locations, there are zones of interbanded, fine-grained, massive, pale-grey, biotite speckled psammite & medium to coarse-grained, feldspar augen pelite. Pelite bands range from a couple of centimetres to 60 centimetres. Fibrolite foliae wrap around feldspars & become knotty in places. Feldspars may be 'wrapped' by fibrolite-biotite foliae and are often retrogressed to muscovite. 0.5-1.5mm garnets form a part of the schistosity and very fine garnets are included in the feldspars. Fine wispy to flame shaped fibrolite bundles are seen in some pelitic zones.

Feldspar augen are common constituents of pelitic units in areas that have undergone deformation during D3A and can occur in clastic metasediment sequences that show no other sign of D3 deformation. It is possible that in psammite-dominated sequences or zones such as that between ALL and 2L in the NBHC area, pelitic interbeds form the locus for all relative movement while the more competent psammitic units (or the GQH) remain competent. All rotational strain may take place along the pelite bands with the result that the feldspar augen grow and are deformed during D3A.

#### 5.6.7 The Thomson Shear Zone.

The Thomson Shear Zone (TSZ) is a major D3A structure lying to the south of and parallel to the shears of the BOA System (Webster, 1994a). It comes into prominence in the northeast-central region of the mining field where it transects the orebodies in the Blackwoods-Browne Shaft area of the British Mine (ML 16) (e.g. Figure 5.12). It produces a 250-300 metre sinistral, west block up offset of 2L and 3L and severely attenuates the British Antiform; virtually truncating it at depth. The TSZ it is exposed in the north wall of the Blackwood's open cut and dips 65 degrees to the northeast (van der Heyden and Edgecombe, 1990). The TSZ is less well understood than the BOA due to poor mine exposure. It was not recognised by Gustafson (1939) who interpreted the intense planar zone and its effects on the orebody as the result of plastic flow and exaggeration of the "Eastern Syncline". Surface outcrops of mineralisation within the TSZ are composed of fine-grained saccharoidal quartz and gossanous material that are very similar to attenuated mineralisation within the BOA (Webster 1994a).

The Thompson Shear is offset by the multiple planes of the D3B British Fault; a structure that is associated with vuggy Thackaringa Type veins and intense muscovite

development and which was reactivated during D4 (van der Heyden and Edgecombe 1990) (e.g. Figure 5.12).

Gustafson (1939) did not recognise the Thompson Shear but attributed the intense planar geometry of the orebodies within this zone to plastic flow during intense folding. This is a general feature of their work; where they failed to recognise much of the intense shearing within synforms on the southern side of the orebodies; attributing this to 'flowage' during folding.

#### 5.6.7.1. *The British Orebody.*

The British Orebody is a large shear and fault bounded block of primary rhodonic 3L mineralisation which is hosted within the TSZ but which is continuous with the main mass of the orebody (Boots, 1972) via sheared and thinned belts of mineralisation. It preserves the F2 fold geometry of the British Antiform in part, within the main mass of the orebody but it has been mechanically mobilised and offset by D3A shearing along the Thompson Shear, and then further dislocated by later D4 faulting (the British Fault). The British Orebody is separated from other significant ore zones within the Thompson Shear Zone, such as the King Shaft Orebody, by D4A fault planes of the British Fault Zone (see below).

Boots (1972) recognised two major types of ore textures within the 'British Orebody', which he termed prograde and retrograde. The prograde textures consisted of equidimensional grains of sulphide and gangue with common straight to slightly concave grain boundaries, triple junctions and small grains of gangue minerals commonly found at the triple junction points (textures observed by the Webster, (1994a) in all Stratiform and most Mobilised styles of mineralisation). Retrograde types consisted of schistose sulphides and mineralisation of equigranular grainsize but in which sphalerite grains tended to be fractured, variably rounded and 'wrapped' in steely galena foliae (textures observed by Webster (1994a) in mineralisation associated with late brittle faulting).

Boots (1972) described preferential mobilisation of minor amounts of copper, cobalt and nickel and attributed the presence of silver-antimony-arsenic rich carbonate veins in fault zones to preferential mobilisation as well.

#### 5.6.7.2. *Upper North Mine levels.*

In the upper region of the North Mine, 3L is intensely transposed within the TSZ (at least to the 8 Level sill, see maps NTH1 to NTH8 in Appendix 1). Down plunge to the northeast, 3L gradually leaves the TSZ, which passes away the west. The orebody trends several degrees more northeasterly and as it moves further from the influence of the shear, it preserves a more obvious pre-D3 folded geometry and the elongate, tabular form diminishes.

#### 5.6.7.3. *F3 Folds.*

F3 folds are developed within and adjacent to D3A (and possibly D3B) shear zones within the BOA and Thompson Shears. They are generally small-scale structures with amplitudes in the order of half a metre to 15 metres and plunge to the southwest (Figures 5.25 & 4.13).

All F3 structures within the mining field are closely associated with D3A shears, particularly the BOA. Folds have been observed on the 20 Level 48 metre contour at NBHC associated with the WZS and in the South Mine in association with the Main, Channel and Central Mine shears (e.g. 970 Level, see map NBH6 in Appendix 1).

F3 folds are generally isoclinal and have a strong S3 axial planar cleavage that is characterised by needle-like sillimanite development within strongly differentiated biotite in pelitic layers (Figure 5.25). Ore in the shear zones associated with F3 folds has layers of quartzitic gangue, presumed to be metasomatic (e.g. South and Pasminco Mines). F3 folds have the following characteristics:

1. They are associated with shearing on orebody margins, at points where major shear planes merge or lie in close proximity,
2. They contain sillimanite within a strong S3 axial planar foliation,
3. They occur at points where high strain zones intersect at orebody margins (such as the zone where the Main and Central Mine Shears merge), and
4. They are mostly shallow to steeply southwest plunging.

South plunging folds identified by O'Driscoll (1968) on the western side of the upper levels of the North Mine and similar types of folds in the British Mine area and



northeastern Block 14 Mine on the northern side of the orebody are interpreted here as F3 folds.

#### 5.6.7.4. *The D3A Globe-Vauxhall Shear Zone.*

The effect of early high-grade D3A shearing becomes more intense in the central-north and northeastern parts of the mining field where the Thompson Shear Zone produced significant low angle attenuation and offset of the orebodies on the scale of hundreds of metres. Similar geometric and textural changes take place within 3L in an attenuated region below the 29 Level of the North Mine (e.g. Figure 5.26 in separate map folder, and see maps NTH26 to NTH34 in Appendix 1), where the Fitzpatrick Orebody is separated from the main orebodies by shearing. This offset has traditionally been attributed to the effects of the D3B Globe-Vauxhall Shear Zone (e.g. Leyh and Hinde, 1990).

However a closer examination of the details of the geology of the orebodies in this region of the mine do not really support a late D3 dislocation model but suggests that the attenuation and dislocation of 3L took place at an earlier stage; probably D3A. This is postulated to be the result of an 'early' D3A stage of movement on the Globe-Vauxhall Shear Zone, or another structure that is analogous to the Thompson Shear. The evidence for this suggestion is discussed below.

The retrograde shearing and the predominant muscovite-biotite fabric observed in the region of the dislocation are later overprints on an earlier high grade transposed fabric and relate to a later phase and style of deformation. In the zone of offset, the predominant dislocation is a result of intense ductile deformation, such as that which affects 3L and 2L (Figure 5.26). The lead grade distribution within 3L remains remarkably consistent, even where the orebody is completely transposed into alignment with the D3A structural fabric. Lead grade (defined by galena distribution) forms a distinct D3A S3 foliation that parallels the zone of transposition and shearing and the grain of this trend is overprinted by the later muscovite-biotite shear fabric.

The galena-defined "cleavage" fabric within the orebodies near the 30 Level North Mine, where the orebody is strongly planar and thinned (it is truncated by shearing below the 32 Level), is continuous, well-defined and parallel to the elongation of the orebody (Figure 5.26). The internal galena-defined fabric and the annealed textures of

the ore show that the orebody was attenuated at high grade before being affected by the lower grade quartz-muscovite-biotite defined shearing of the D3B Globe-Vauxhall Shear Zone.

Remnant fold geometries defined by gangue distribution within 2L and 3L; the distinct mineralogy and grade variations of 3L and 2L and the grade distribution of the pre-shearing orebodies and folds is preserved on the 32 level, where both orebodies have been transposed into a single lenticular 'sheet' of ore by the shearing. In the southwestern part of 3L, the high-grade core of the orebody is still distinctly visible and the calcitic gangue of the 2L orebody is present in the northeastern segment (see map NTH32 in Appendix 1).

The implication of these observations is that the structural offset that takes place in the orebodies in the lower levels of the North Mine has been caused by a zone of high strain, developed at high metamorphic grade; probably D3A (or even D2). This interpretation of the evidence also suggests that the orebodies were structurally attenuated and offset before the development of the generally recognised intense D3B retrograde shearing associated within the Globe-Vauxhall Shear Zone. Therefore, the movement indicators and structural analyses that have been undertaken on the retrograde Globe-Vauxhall Shear Zone only reflect the last component of the movement that has taken place between the 32 and the 36 Levels of the North Mine and also, by inference, that which has taken place between the Fitzpatrick orebody and the "2K" Zone.

D3A attenuation and shearing also strongly affected the common limbs of isoclinal F2 folds within in the North Mine, transposing 2L and 3L, especially at ore-metasediment contacts. However, the distinction between D3A and D2 is not so clear as in the Pasminco Mine and South Mines and the two events appear to overlap in style. This may be due to the greater intensity of F2 folding in the northern part of the deposit, which resulted in earlier onset of shearing and transposition.

#### **5.6.8. D3B Quartz-Muscovite-Biotite Shearing.**

Retrograde quartz-muscovite-biotite shearing (D3B) was widespread throughout the BH Block during the waning stages of the Olarian Orogeny. It produced discrete planar zones of variably biotitic and garnetiferous quartz-muscovite-biotite schist that

were formed at lower amphibolite grade (Vernon and Ransom, 1971). Many of the structural fabrics developed in D3B were initiated during the final stages of D3A and the two events show a transitional spectrum of features.

Within the Pasminco Mine, D3B shearing was commonly focussed along planes of D3A attenuation and transposition (Webster, 1994a) and this is the case elsewhere on the field. It is interpreted to represent the lower grade continuation of D3A. D3B was particularly strong in the southwest and northeast ends of the deposit while the central regions appear to have largely escaped significant D3B effects.

D3B shearing further modified the original F2 fold geometries and produced muscovite schistosity along many lithological contacts. D3B shearing was best developed in association with the most strongly attenuated regions of the orebodies (such as the southern margin of 2L and 3L in the southwestern half of the deposit). D3B shearing accentuated and occasionally boudinaged the tabular bodies of D3A mobilised sulphides ('Droppers') resulting in discrete D3B quartz-muscovite-biotite margins to these D3A structures.

Important structures active in the area of the main orebodies during D3B include:

#### **1. Northeastern Part of the Mining Field:**

- The Globe-Vauxhall Shear Zone,
- The Western Shear Zone,
- The DeBavay Shear Zone, and
- The Lord's Hill Shear.

#### **2. Southwestern Part of the Mining Field:**

- The Main Shear (South Mine to ZC area). The term "Main Shear", as originally defined by Gustafson (1939) has come to be used by mine geologists in the Pasminco Mine to refer to the quartz-muscovite-biotite shear zone and associated brittle joint and fracture system located on the southern margin of the orebodies in the Pasminco Mine. This definition was adopted by Webster (1993; 1994a) and differs considerably from the definition of Gustafson (1939; 1950; 1952) (see below) and subsequently discussed by Rothery (2001). The definition of "Main Shear" used throughout this thesis will more closely reflect

the original meaning of Gustafson (1939). The Main Shear merges with the Western Zone of Shearing to the southwest of the NBHC area of the mine.

- The Termination Schist Shear (Pasminco Mine),
- The Central Shear (Pasminco Mine),
- The Retrograde Main Shear (Pasminco Mine),
- The Retrograde Main Shear (Southern Cross area of Pasminco Mine - WZS), and the
- Later phases of movement of the 'Dropper' Shears.

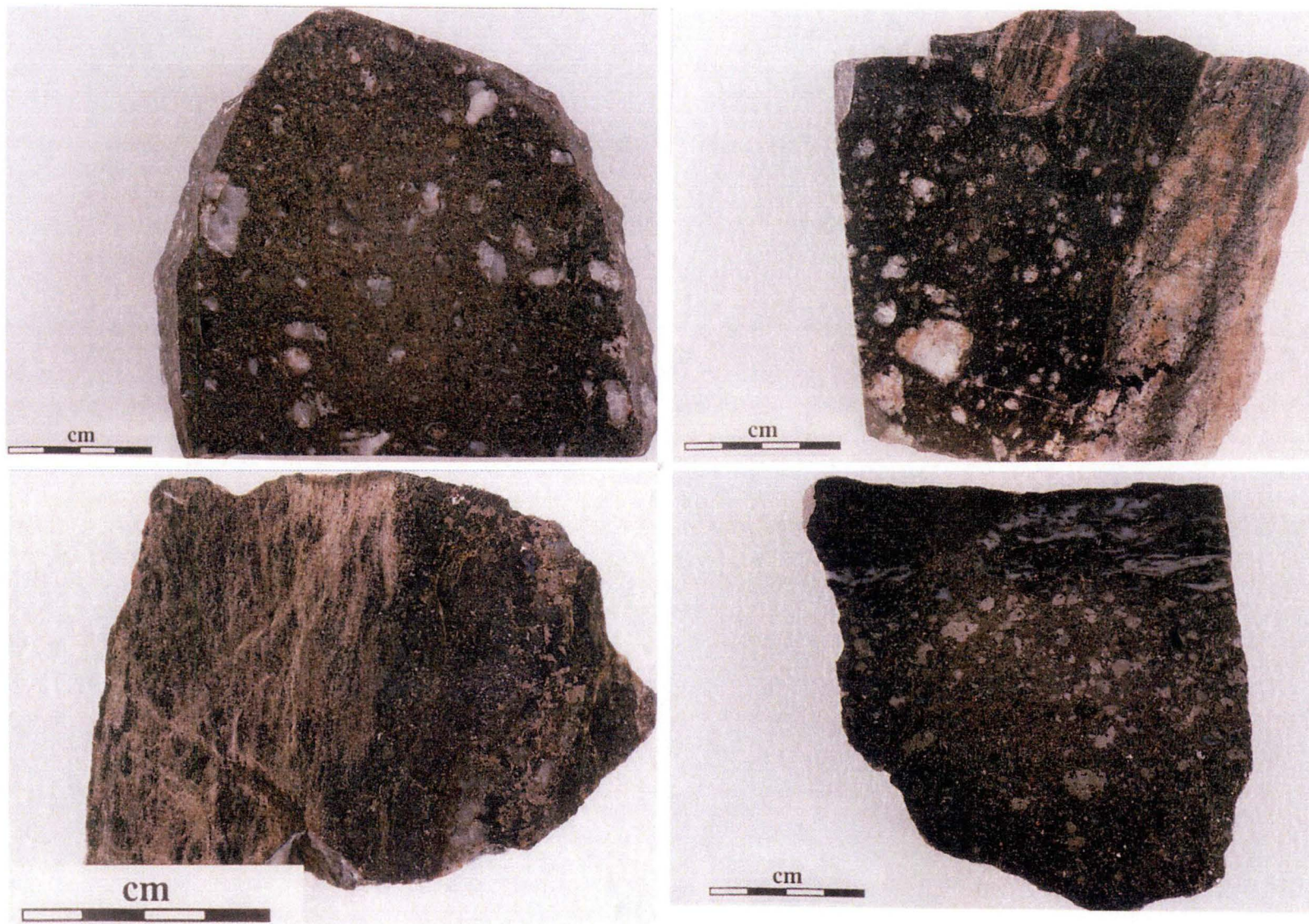
#### 5.6.8.1. *The effects of D3B within mineralisation.*

During D3B, white quartz veining developed at ore contacts (and was often dismembered) and schistose sulphides were formed at the margins of mineralisation. There was widespread development of rolled and 'pebble' textures in sulphides (often durchbewegt texture) (Figure 5.27a & b).

Amphiboles were crystallised as early phases within D3B shears, probably as a continuation of D3A processes. Asbestiform, pale-khaki to olive green to dark green cummingtonite was developed within the matrix of attenuated, weakly friable, siliceous, saccharoidal textured ore in Southern A Lode (Figure 5.28a) and within deformed quartz veins in southwestern BL, in the Southern Cross area of the Pasminco Mine (Figure 5.28b). Skeletal, ragged cummingtonite crystals were found on the 16 and 17 Levels, within a matrix of saccharoidal quartz (silicification) on the southern attenuated margin of B Lode, in the Southern Cross area of the Pasminco Mine. Cummingtonite is also a common accessory mineral in silicified and altered pegmatite on the margins of B Lode in the Southern Cross area of the Pasminco Mine.

Acicular, dark green actinolite occurs in 2L mineralisation at the initiation point of the 'Western Dropper' within the Main Shear on the Pasminco Mine. The late-stage actinolite at this locality is formed along hairline fractures within rounded clasts of white vein quartz and wall rock within durchbewegt textured ore (Webster 1994a). Actinolite also rimmed many of the rounded wall rock clasts within the deformed ore. The actinolite and vein quartz mineralogy described in the Axial Plane Orebodies in the B Lode Shear by Stockfeld (1993d) is similar to that observed in 2L on the 21 Level. Haydon and McConachy (1987) recorded cummingtonite and grunerite in the garnet





**Figure 5.27.** Photographs of a series of polished slabs of intensely deformed sulphide-rich rocks from various localities on the Broken Hill mining field.

**a.** BHD3. 'Pebble ore' comprised of rounded white and blue vein quartz clasts in a medium-grained equigranular sulphide matrix. From the upper limb of 1L/2L, within the BOA Shear system (where they are merged within the D3A Main Shear), southern margin of the orebodies, 10 Level, ZC area of the Pasminco Mine.

**b.** BHD 10. Pebble ore comprised of rounded white and blue quartz clasts and fragments of banded and garnet altered wall rocks, in a fine to medium-grained equigranular sulphide matrix). This specimen is from a position adjacent to strongly retrogressed (muscovite-biotite) wall rocks and probably comes from within or near a major D3B shear zone. North Mine, locality unknown but probably from deeper mine levels (Fitzpatrick area). Note rounded clast of banded and garnet altered wall rock near top edge of specimen.

**c.** Pyrrhotite-rich specimen of sphalerite-rich ore in association with muscovite altered wall rocks (pale brownish grey). From the margins of 2 Lens, NBHC area of the Pasminco Mine.

**d.** Arsenopyrite-rich sphalerite mineralisation with coarsely annealed texture. This specimen is from a tectonically thinned part of 3 Lens, 20 level of the ZC mine. Arsenopyrite is a common constituent of D3A mobilised ores and commonly impregnates the matrix of garnet sandstone adjacent to 2L in the Pasminco Mine.

quartzite of the Western Mineralisation, suggests that this zone has also been affected to some degree by D3A/D3B shearing.

The spatial association between amphiboles and metasomatised, strongly attenuated regions of orebodies (Webster, 1993, 1994a & b) places the formation of these minerals during D3. The occurrences of amphiboles observed are in D3A shears, where quartz-muscovite-biotite shearing is weakly developed (usually as a weak retrograde foliation, if present) rather than as discrete shear planes. This observation, and the late fracture filling habit of acicular actinolite and the fibrous habit of cummingtonite, is interpreted to show that the amphibole phases formed during the latter stages of D3A to early D3B shearing. These phases were probably formed during greenschist to lower amphibolite facies retrograde metamorphism.

D3B shearing was developed within the attenuated and dissected limbs of the ZCA and NBHCS and along the eastern margin of S1L and BL in the Pasminco Mine. The Western Zone of Shearing became a locus of D3B shearing on the Southern Cross Shaft area. A major D3B shear known as the Termination Schist modified the F2 geometry of ALL and 2L within the WKS (Webster, 1994a). In the North mine, intense D3B shearing was developed adjacent to, and to the north of 2L and 3L as the Globe-Vauxhall and Western Shear System. This system offsets the Fitzpatrick Orebody (Leyh and Hinde, 1990) from the main orebodies and truncates 2L and 3L at depth. The orebodies have been located to the north of these structures as the "2K" ore zone.

## 5.7. THE FOURTH DEFORMATION.

### 5.7.1. Introduction.

The fourth deformation to leave identifiable effects within the BH mines area (D4) was associated with the widespread development of brittle faulting, jointing, localised hydrothermal activity and folding (Webster, 1994a; 1996b, this study). It took place during the Delamerian Orogeny (455-520 Ma), a regional scale tectonic period in which brittle faulting was widespread throughout the Broken Hill Domain (Stevens, 1986). D4 did not generally exceed greenschist grade (Webster, 1996a) though higher temperatures occurred locally and generated pyroxenoids and pyroxenes in some faults in both the Pasminco and North Mines (e.g. Worner & Segnit, 1988). It took place during the second metamorphic event to leave evidence in the orebodies (M2).

The effects of D4 within the orebodies have two distinct phases (Webster (1994a, 1996a & b; this study);

D4A, which was a distinct medium to low temperature (greenschist to lower amphibolite) event associated with folding, dolerite intrusion, hydrothermal activity in faults, minor sulphide mobilisation, weak ductile deformation of ore and dolerite dykes and siderite-galena-quartz vein formation. And,

D4B, which was a later, low temperature faulting event (sub-greenschist to greenschist) that was characterised by the development of brittle, chloritic faulting, jointing, pug zones, milling of ore, vugh formation, jointing, secondary calcite and pyrite deposition in faults and joints and biotite alteration of dolerite dykes.

At mining field scale, D4 produced a series of brittle fault zones that crosscut lithological boundaries and often exploited Olarian retrograde shears. D4 fault planes were the focus of some hydrothermal activity and alteration of gangue.

Local refolding took place in the Broken Hill area, particularly focussed in the centre of the mining field. D4 was associated with significant ductile deformation in the orebodies in which earlier intruded dolerite dykes were dismembered and dislocated. Dolerite dykes in wall rocks adjacent to the orebodies were subject to biotite alteration. Associated with D4 was extensive metamorphic fluid activity, which altered plagioclase to garnet in the margins of the deformed dolerite in ore, and pyroxenoids were crystallised in vughs in some fault zones at both the northeast and southwest ends of the mining field.

On a regional scale, D4 may have been associated with gentle refolding of the Willyama Supergroup on NNW-SSE axes (Webster 1996b), reactivation of D3 shears, the generation of the Thackaringa Type quartz-siderite veins and the intrusion of a north-west trending dolerite dyke swarm (which also intruded the orebodies) (Stevens 1986).

D4 faults were originally considered to closely follow the closing stages of D3 (Webster 1993, 1994a). However further work has shown that they are of Delamerian age, post-dating the intrusion of the dolerite dykes and are associated with Thackaringa Vein





*Figure 5.28. Fibrous cummingtonite within weakly friable saccharoidal (silicified) high grade A Lode ore. Cummingtonite comprises the pale cream to greenish brown to khaki fibrous material in the band below the pen top. It is most abundant in the sulphide-rich regions of the specimen. This development of cummingtonite is located adjacent to garnet sandstone altered garnet quartzite. Sub-mm red garnets are speckled throughout the ore and there is a weak banding defined by saccharoidal quartz and sulphide abundances.*



*5.28a. Massive fibrous cummingtonite within fractures in clear vein quartz. Locality is adjacent to B Lode, 17 Level, Southern Cross area of the Pasminco Mine. C = cummintonite, q = clear vein quartz..*



styles of mineralisation. D4 fault movements must therefore post-date the initial stages of the Delamerian Orogeny.

Joint sets and differential movement at some lithological contacts were also developed throughout the mines area during D4, particularly in a northwest-southeast orientation. A possible example is the Zogiew Fault (the Morland's Fault of Morland & Leever, 1999) in the Potosi-Silver Peak area of the northern leases. An applied potential survey conducted in November 1995 (Pasminco Mining unpublished data, November 1995) confirmed that a break between the Potosi Extended mineralisation and the Potosi C Horizon was probably due to this fault.

The development of faults and joint sets and reactivation of earlier shear zones has had important implications for ground conditions in underground mining operation.

A summary of the major features of D4 is presented in Figure 5.29.

#### **5.7.2. Definition of D4 Fault Zones.**

D4 faults are readily observed in underground workings, in drill core and in surface outcrops. D4A faults are characterised by the following features:

- They can be directly observed in underground workings and be recorded in mapping as transgressive fracture planes and distinctive vein and breccia systems (e.g. Boots, 1972, Lawrence, 1968a, Webster 1993),
- They contain siderite-galena veins in places, as well as other unusual minerals (e.g. sturtite, rhodocrosite and, on rare occasions, rhodonite and 'hairy' bustamite) and may be associated with zones of wall rock alteration,
- The extrapolation of apparently minor structures between exposures in underground openings (between "outcrops") allows the identification of large-scale trends that explain offsets in units that are observed in plan and longitudinal section views, and
- They dislocate and offset stratigraphic markers, as well as the orebodies, in some areas, such as the Menindee Rd area,

In underground workings, D4B faults are characterised by anastomosing sinuous joint and fault planes with associated puggy, chloritic and milled zones, and fragments and blocks of broken material. They usually have slickensided surfaces. They may range

<p><b>Summary of the features of D4A (DELAMERIAN OROGENY)</b></p> <p>Brittle, hydrothermally Active Fault Systems &amp; Associated 'Drag' Folding.</p> <p>D4 faults have exploited several significant D3A shear zones &amp; systems (reactivated) including:</p> <ul style="list-style-type: none"> <li>• DeBavay</li> <li>• Early Lords Hill Fault</li> <li>• 'prograde' Main Shear &amp; similar structures in southwest</li> <li>• the early stages of the development of the Central &amp; Flat Faults &amp; Lords Hill Fault. Other structures are probably the same.</li> </ul> <p><b>Structures</b></p> <p>Forms hydraulic breccias, laminated vein systems, tension vein systems &amp; alters wall rocks &amp; gangue in localised areas around fault &amp; vein margins (e.g. 2L &amp; amphibolite adjacent to the Consols Lode).</p> <p>Offset of the NE region by British Fault Zone – approximately 500-750m. Offset of D3A Thompson Shear in Browne Shaft Area</p> <p><b>Intrusion of fine-grained dolerite dykes into mineralisation along NW-SE plane.</b> Minor mechanical sulphide mobilisation in ore – dolerite dykes dismembered.</p> <p><b>F4 folding</b> traverse mining field in the Block 14 &amp; British Mines (especially). F4 gently refolds the mining field &amp; all previous structures on NW-SE axis. Pegmatite veins develop in F4 hinges. F2 folds in MinSeq are now SW plunging at SW end, NE plunging at NE end of deposit. Undulations elsewhere may also be F4.</p> <p><b>Alteration &amp; mineralisation</b></p> <ul style="list-style-type: none"> <li>• Hydrothermal activity along faults produces laminated veins.</li> <li>• Rhodonite, bustamite (including fibrous &amp; 'crustiform' varieties), hedenbergite &amp; rhodocrosite form as cavity fills in some faults &amp; cavities during hydrothermal activity.</li> <li>• Hydrothermal veining &amp; gangue mineral alteration in 2L in Pasmunco Mine &amp; 3L in North Mine associated with carbonate &amp; sturtitic alteration of rhodonite-bustamite near fault systems.</li> <li>• Formation of ABH Consols siderite-silver vein at intersection of D3B fault splay &amp; Consols Amphibolite units Galena-quartz-siderite veins in lower levels of British Mine.</li> <li>• Minor hydrothermal activity in orebodies - garnet alteration of dolerite dykes &amp; sulphides impregnate dolerite fragment margins. Minor fluid phase sulphide mobilisation (pyrrhotite, chalcocopyrite &amp; minor galena mobilisation).</li> <li>• White quartz veining &amp; silicification of some pegmatite. Wall rock bleaching-silicification, sericitisation &amp; coarse muscovite in wall rocks of veins and faults.</li> <li>• Manganocalcite-bearing angular fault breccias, with fracture associated amorphous hydrous manganese silicate (sturtite) alteration of rhodonite in 2L. Some silicification of rocks adjacent to fault zones</li> </ul> <p><b>D4A: Locally lower amphibolite grade &amp; possibly higher in hydrothermal systems?</b></p>	<p><b>Summary of the features of D4B (DELAMERIAN OROGENY)</b></p> <p>Late-stage faulting, joint &amp; fracture systems</p> <p>Reactivation or continuation of D4A.</p> <p><b>Structures</b></p> <ul style="list-style-type: none"> <li>• Late-stage faulting with chloritic, brittle &amp; puggy stages of movement (e.g. later stage of movement on the Flat Fault &amp; Central Faults in the Pasmunco Mine, which were the most significant fault sets, in terms of ground conditions, in much of the 2L mining area).</li> <li>• Pug-lined joint &amp; fracture systems. Jointing throughout the deposit.</li> <li>• D4B faults often exploit &amp; overprint D4A faults &amp; tend to be focussed in pre-existing shear zones, generally destroying or mulling D4A features.</li> <li>• However, they may crosscut all other structural fabrics.</li> <li>• Diffuse joint &amp; fracture sets may exploit lithological boundaries forming 'slabby' ground. Probably the cause of the extremely poor ground conditions in the Fitzpatrick Orebody.</li> </ul> <p><b>Associated minerals.</b></p> <ul style="list-style-type: none"> <li>• Chloritic, puggy &amp; muscovite altered fracture planes, with deformation of D4A features</li> <li>• Some schistose (sheared) sulphides</li> <li>• Some mulled ore</li> <li>• Chloritic faults, shears, pug zones &amp; mulled ore.</li> <li>• Secondary calcite ('often dogs tooth') lining vughs &amp; cementing fragments.</li> <li>• Pyrite along fault planes, vughs &amp; joints</li> <li>• Jointing &amp; faulting throughout the deposit.</li> </ul> <p><b>D4B: Greenschist grade.</b></p>
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**Figure 5.29.** Summary of the features of the third deformation (D3) within the Broken Hill mineralised system & Mine Sequence.

from a dispersed joint set to a narrow (less than 2m wide) fault zone. Broken zones are mostly re-cemented by later calcite, especially within or near 2L, 1LL & 1LU. D4B faults usually overprint earlier veined and hydrothermally altered fault zones (D4A). D4B faults were of particular interest to the mining companies because they were an important cause of poor ground conditions in the workings. Consequently, these features have been more comprehensively recorded in routine geological mapping than all other structures.

### 5.7.3. Styles of D4 Faulting.

Two styles of fault were formed during D4; those structures that developed within pre-existing D3A-B shear zones and those that show no pre-existing lithological controls. Both styles of faulting developed in D4A and D4B. Important structures are outlined below.

#### 5.7.3.1. *Reactivated Olarian D3 shears.*

Important examples of reactivated Olarian D3B shears in the mines area include;

- The Central Fault: Partly exploits a pre-existing D3B shear that was developed in the metasediments in the footwall of 2L as a component of the Main Shear. However, the Central Fault also dissects 2L, 1LL, 1LU where it produced very bad ground conditions, including the 'Pug Zone' on the overwall of 2L in the Pasminco Mine (Figures 4.35 & 4.36). The D3B Central Shear did not transect the mineralisation but the later D4A/D4B Central Fault did, producing alteration and veining within 2L. It produced milled mineralisation, schistose (steely) galena and pug (Webster, 1993).
- Brittle stages of movement along established D3 structures such as the Termination Schist Shear and the Main Shear in the Pasminco Mine.

#### 5.7.3.2. *'New' D4B structures.*

D4B faults that do not appear to have exploited pre-existing shear planes include;

- The Flat Fault and its subsidiary planes in the Pasminco Mine. This fault transgresses all pre-existing structural fabric (see maps NBH20 and NBH21 Appendix 1).
- The Cumming Fault in the North Mine (e.g. Figure 4.22),

- The Adam Fault in North Mine (e.g. Figure 4.22 & 4.23).

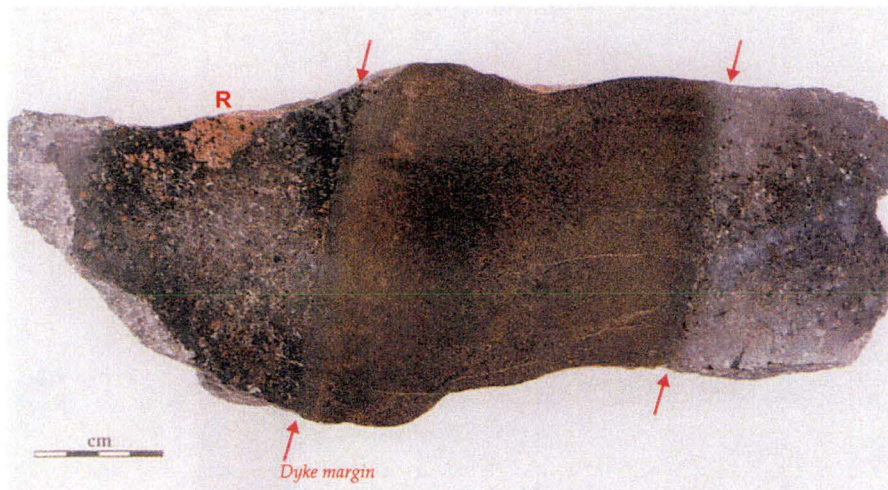
#### 5.7.4. D4A Faults.

Late faults are widespread throughout the Broken Hill mining field as discrete planes, complex fault zones, as fault arrays and as more dispersed joint sets and fracture systems. D4 shearing and faulting defines a fan-like fault and shear array that transgresses the mining field at progressively shallower angles from northeast to southwest. Components of this system include the British Fault, DeBavay Shear and the Willy Willyong Shear. The system seems to be related to the Globe-Vauxhall and Western Shear systems that mark the northern margins of the mining field. The system is east to southeast dipping with east-northeast block up reverse sense of movement.

The greatest development of D4 structures is focussed in four discrete belts within the mining field which, from northeast to southwest, are the Round Hill Zone (trending approximately grid north-south), the DeBavay Zone, the British Fault Zone (trend north-south to slightly southeast-northwest) and a more dispersed southwestern zone (trending northeast-southwest) (Figure 5.14). The most important of the four zones is the British Fault Zone, focussed in the British-Junction region of the field (Thompson-King-Browne Shaft workings).

D4A is characterised by brittle faults in which hydrothermal alteration and the formation of manganocalcite-sturtite-(rhodocrosite)-bearing laminated fault and vein systems took place in all parts of the deposit (Figure 5.30c). Hydrothermal alteration along D4 faults within the orebodies coincided with alteration of dolerite dykes in mineralisation (and the development of the Thackaringa Type galena-siderite veins (eg. the ABH Consols Lode). D4A (Webster 1996a) corresponds to the earlier phase of "G2C" faulting described by Webster (1994a, b).

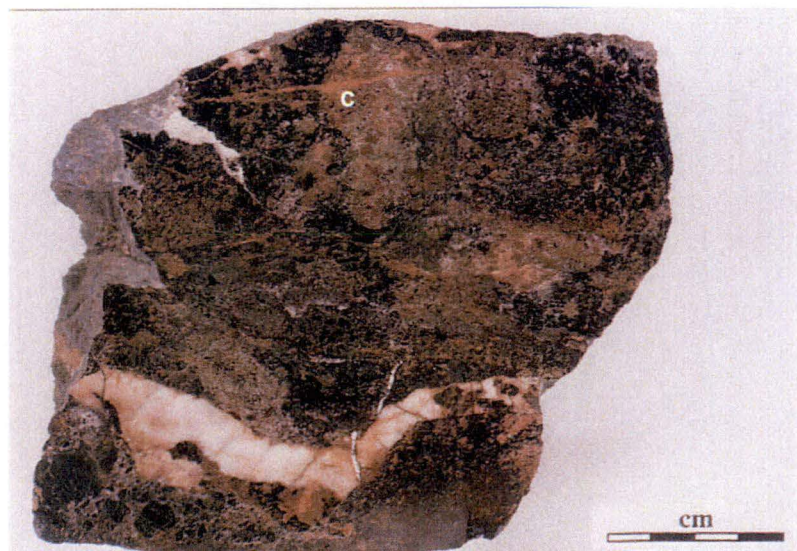
D4A faults formed at relatively high temperatures. They often have a relatively high-grade mineralogy in some cavities and fracture systems. In the northeast of the mining field, "hairy" bustamite was commonly found in faults and fractures, often overgrowing, or loosely coating gem quality hedenbergite crystals on the margins of cavities (e.g., Worner & Segnit, 1988; author personal observation). Bustamite also formed complex asbestiform layered coatings on cavities (e.g. Birns, 1968). In the



**Figure 5.30a.** Polished slab with D4A dolerite dyke intrusion in high grade 3L ore. North Mine. Note the light coloured dyke margins (garnet altered and galena impregnated) & the pink rhodonite clasts(R) in the ore in top left of view. Locality unknown but (probably from pillar mining areas between 26 & 28 Levels).



**5.30b.** D4A inesite (I) within a fault plane within banded calcitic ore. 2 Lens, Pasminco Mine. Fault plane shows later slickensiding.



**5.30c.** Polished slab of D4A brecciated ore (rounded clasts of gangue in sulphides - e.g. C) containing at least two generations of quartz veins (white). Central Fault, 20 Level Pasminco Mine (2L). Sturtite (black) in matrix (alteration product of rhodonite).



southwest of the deposit, in the Pasminco Mine, gem quality rhodonite was found, associated with bannisterite, in cavities on the 12 Level (e.g. Worner and Segnit, 1988). Rhodocrosite is also a common cavity infill phase in faults in the orebodies. The formation of such minerals within cavities in a fault zone shows that, at least locally, temperatures associated with open space fault and fracture systems were high enough to generate pyroxenes and pyroxenoids and confirms that the minimum temperature stability of Mn silicates is poorly known.

Significant D4A faults that were developed within the mineralised system were (refer to Figure 5.14, in separate map folder):

1. The DeBavay Zone (northeast end of mining field, a reactivated D3B shear),
  - The Lords Hill Fault (a later D4B splay off the reactivated D3B DeBavay Shear).
  - Elements of the Globe Vauxhall & Western Shear System?
  - The Adam Fault (D4B splay off the reactivated D3B DeBavay Shear).
  - The Cumming Fault (D4B splay off the reactivated D3B DeBavay Shear).
2. The British Fault Zone (central northeast of the mining field). A complex fault zone with multiple planes with associated, strongly developed F4 folding. Development of this zone also included the formation of related siderite-galena veins (including the ABH Consols Lode within the Consols Amphibolite).
3. The Southwestern Zone;
  - The Central Fault,
  - The Flat Fault,
  - Fault and joint plane reactivations within the Main Shear and BOA Shear System.
  - Cross faulting within the Kintore Open Cut?
  - BHP area ("horses" and "intrusions" of wall rock juxtaposed with ore in the BHP mine suggest some fault offset of the orebody in this area) (illustrated in Jamieson & Howell, 1893).

Most fault systems have a strike within 20 degrees of north and have a sinistral sense of offset. Movement on D4 faults is variable, from a few centimetres to hundreds of metres. The British Fault Zone causes a 350-500 metre sinistral offset of the orebodies and the D3A Thompson Shear in the British Mine Area (e.g. Figure 5.1). No 2 Lens is displaced between 50 and 100 metres by movement along the Lords Hill Fault (possibly with an earlier D3B component of movement), between the 23 and 29 levels of the North Mine (e.g. Figure 5.10, 4.22 to 4.24 and see maps NTH23 to NTH29 in Appendix 1).



The following discussion is focussed on those faults for which new information has been obtained during this study.

#### **5.7.4.1.      *The British Fault System.***

The British Fault (D4A/D4B) is focussed in the Menindee Rd area of ML 16, in British-Junction region of the mining field (Figure 5.1 & 5.14). It consists of at least three distinct fault planes that offset the D3A fabric of the Thompson Shear in a sinistral, northeast block up (reverse) sense. Each plane of the British Fault dips steeply east to northeast (approximately 60° to 70°), has a sinistral sense of movement and has a northeast block up sense of movement. The effect of the fault in 3L is that movement along the structure has caused the north-eastern region of the orebodies to be raised at least 200 metres in a vertical sense, relative to the southwestern part of the deposit. The British “Shear” was recognised as being, at least in part, Delamerian (D4) in age by Van der Heyden and Edgecombe (1990). The structure has been re-defined as a fault comprising at least three separate but significant planes of dislocation that all have a similar sinistral offset and steep northeast to eastern dip.

The British Fault Zone is closely associated with a series of gentle F4 folds that are referred to in this study as the ‘Menindee Road’ folds. F4 folding deforms the D3A fabric of the Thompson Shear, the ore hosted within it and the surrounding strata of the Mine Sequence (see below). Vuggy Thackaringa Type galena-siderite veins are formed in fractures and veins associated with the British Fault in the lower levels of the British Mine (see map BRIT1200 in Appendix 1). The flat dipping Consols galena-siderite lode, hosted within the Consols Amphibolite, lies within the British Fault and its associated zone of F4 folding.

#### **5.7.5.      D4A Folding.**

Form surface mapping (and form surface extrapolation) of the surface of the BH mining field has revealed a series of asymmetric, open style folds that transect the orebodies in the British-Junction and Central regions of the mining field. The folds strike approximately northwest to west and plunge towards that direction (Figure 5.1, in separate map folder). F4 folds deform the Thompson Shear, and the shear hosted ore contained within it, and produce local undulations and plunge reversals in 3L in the upper levels of the North Mine.

Laing (1977a) recognised a generation of mesoscopic folds in the mines area that he defined as F4. The structures he identified were confined to mesoscopic scale and were asymmetric, dextral, and shallow southwest plunging, with wavelengths of between 0.5 and 2 metres. Axial planes dipped moderately southwest, west or northwest. Laing's (1977a) F4 folds refolded D2 structures and overprinted some S3 shears and sillimanite fabrics in several locations and by the fact that several occurrences of F4 folds coincided with steeply dipping faults that were parallel to the S4 axial plane. The folds are open, parallel and smoothly curved with some examples tending to sharp hinges. Laing's (1977a) F4 axial planes lacked a penetrative surface and were defined by jointing or fracture, and commonly contained one or two thin pegmatite veins in the hinge plane. Laing (1977a) stated that the characteristics of F4 folds were consistent with formation in a low temperature, brittle environment relative to D3. Laing's (1977a) D4 folds are correlated with D4A folds on the basis of their overprinting relationship with earlier events, their general constant transgressive trend, their association with fault zones and because of their brittle nature.

F4 folds are also observed at in the upper levels of the British, Junction and North Mines. Attenuated 3L ore within the plane of the Thompson Shear is now sinuous in strike, defining the axes of a series of small F4 folds. Each fold hinge is associated with a plane of the British Fault and the fold style is probably 'drag folding'. *En echelon* fault planes may have been reactivated, and accommodated some of the refolding by plane slippage.

F4 folds persist to depth in North Mine, though they are less common and they become weaker in amplitude. The 'Burrell Bend' fold on the 20 Level (Henderson, 1953) is interpreted here to be an F4 cross fold associated with the reactivated Lords Hill Fault (see map NTH20 in Appendix 1). Undulations with an open style that are observed in form surface trends, and in the orebody geometry, on the deeper mine levels (e.g. Figure 5.10 and Figures 4.22 to 4.24, all in separate map folder) have similar NW strike to the F4 folds and are also interpreted to be the result of F4 folding.

F4 folding persists well into the Block 14 Mine where it causes plunge variations and local minor reversals in F2 folds in 3L (see maps BHP5 and BHP5C in Appendix 1). Low strain zones represented by ore masses within F2 fold hinges were possibly rotated during these events and this would account for some of the variations in

plunge. The cumulative effect of the many F4 folds produces the major plunge reversal in the orebodies that occurs in the Block 14 Mine. All of the Menindee Road F4 folds can be thought of as a single F4 antiform, similar to that envisioned by O'Driscoll (1968) as his "cross fold" or the 'Arch Antiform' of Webster (1993; 1996b). The plunge direction of F2 fold reverses in the Block 14 area, because of the effects of D4 refolding. To the southwest F2 is southwest plunging while to the northeast, they are northeast plunging.

While the intensity of F4 folding in the central region of the field diminishes to the southwest of the British Fault Zone (beyond the Block 14 and BHP Mines) it may be present elsewhere in the mining field. This is particularly likely in the Pasminco Mine, where there are many unexplained undulations in the plunge of the F2 folds and orebodies. F4 folding associated with the poorly defined Southwestern Zone of faulting may produce some of the minor plunge reversals and undulations seen in the orebodies there. They would likely be associated with D4 fault zones.

The first order F2 folds in the mines area, such as the Hangingwall Synform and the Imperial Ridge Synform were also refolded by the 'Arch Antiform', as were 2L, 3L, ALL and the Western Mineralisation. Minor F4 synformal warps occur in the northeastern and southwestern parts of the Hangingwall Synform (especially in the Round Hill and southern leases area). F4 folding has also affected the Broken Hill 'Synform'. It is refolded along the same approximate orientation as the orebodies and the Hangingwall Synform in the central mining field (Webster, 1996b). It now forms a large lenticular dome structure to the southeast of Broken Hill (Figures 5.13 & 4.1). Such large-scale refolding may be associated with the high density of north-south D4 shearing and faulting that is present in this region, and which includes the British Fault Zone, the DeBavay Zone and the Round Hill Zone.

The rocks of the north-eastern part of the mining field and the Pasminco northern leases are still under high strain and underground openings in the deep levels of the North Mine required extensive ground support to maintain mining access and avoid rock bursts. Diamond drilling on the northern leases was constantly hampered by the high stress in muscovite-biotite shear zones. Very large drill rigs (such as the Warman 1500) did not have the power to pass more than 80cm into some shear zones before the extreme strain closed the hole and prevented further penetration.

The evidence presented above suggests that there was ductile folding associated with D4 shearing and faulting and, therefore, that there could have been F4 folding of the scale suggested by O'Driscoll (1968) and Webster (1993, 1996b). It is worth noting that if refolding can take place on a large scale in the mining field area, in association with a post-Olarian fault-shear system, then it shows that the rocks of the Willyama Supergroup were not completely cratonic after the Olarian Orogeny. They could be refolded on a large scale by a cross-folding event. This observation supports the possibility that a refolding event could have affected the entire Broken Hill Domain, at least in localised associations with major fault zones, as was suggested by Webster (1996b). These rocks can be refolded during later events.

No pervasive schistosity was developed in the rocks of the Mine Sequence during D4 folding (S4). However, a number of workers (e.g. Funnell, 1983; Glen, 1978; Willis, 1983, and Stevens 1978) have identified minor D4 structures throughout the Broken Hill Domain, usually consisting of northwest-southeast to east-west trending angular crenulations and minor folds. A single macroscopic F4 fold was defined by Willis (1983). These structures have been interpreted to be of Delamerian age by Webster (1996b). Several workers have also noted that the unconformity between the Willyama Supergroup has been folded in sympathy with the overlying Adelaidean sediments (eg. King and O'Driscoll, 1953; Fenton-Corbett 1978). The Adelaidean rocks are interpreted to have undergone folding during the Delamerian Orogeny (Stevens, 1986).

It has been suggested that a pervasive S4 schistosity did not develop within the Broken Hill Block during the Delamerian Orogeny because regional metamorphism (greenschist facies) was too low to produce significant metamorphic recrystallisation and differentiation within the high-grade rocks of the Willyama Supergroup. It has also been suggested that the level of strain associated with the gentle, open D4 folds was too low to produce a significant schistosity. Only localised occurrences of small-scale crenulations and kink bands were developed (Webster 1996b).

#### 5.7.6. D4A Dolerite Dykes.

Dolerite dykes intrude the Willyama Supergroup in several belts, particularly to the north and west of Broken Hill (Figure 4.1, 5.1, 5.14 and 5.30a). They have been related to the Delamerian Orogeny by Stevens (1986) on the basis of field relationships and

cross cut the dominant northeast-southwest structural grain. Gibson (1997) has referred to the dolerite dykes as the "Broken Hill Dyke Swarm".

Northwest trending swarms of dolerite dykes intrude the Lode Sequence and orebodies in three belts, each with a similar strike to F4 folds. They are mainly focussed in the BHP Mine, near the Delprats Shaft (see Figure 5.1, and refer to maps BHP1 to BHP5 in Appendix 1) and in the North Mine between the 25 and 28 Levels (e.g. Figure 5.10b & c). A third zone of dyke intrusion occurs in the 'embayment area' of the southern leases (Mine Section 340), southwest of the main orebodies (Figure 4.1). A minor dyke occurrence is within metasediments adjacent to the orebodies on the 16 Level of the Pasminco Mine, near the NBHC Service Shaft (see map NBH16 in Appendix 1). There is a spatial association between dolerite dykes, D4 faults and F4 folds (e.g. North Mine).

All dykes cross both Olarian fold and shear trends, and can be correlated with a belt or swarm of dykes discussed by Stevens (1986). Reinterpretation of existing mapping from the North Mine and the BHP areas shows that the dykes transgress the Olarian shears (BOA Shear Zone) and folds (the North Mine Synform). They also cross cut the transposed bedding and alteration in the footwall of 3L in the North Mine.

The dykes that intrude 3L have been deformed and altered (Figure 5.30a). Mechanical sulphide mobilisation associated with weak metasomatic activity, ductile flow and recrystallisation of sulphides and gangue took place within the orebody surrounding the dolerite dykes during D4A. Some dykes were dismembered by ductile deformation to varying degrees within mineralisation and have been pulled apart, producing linear strings of contorted segments within the orebodies. However, the result is only minor dislocation as is seen in the BHP area. On the 26 to 28 levels of the North Mine a dyke has remained intact throughout the main body of 3L (Figure 5.10b & c & 4.22). Fragments of dyke were weakly altered by metasomatic fluid activity in the ore.

All dykes that intrude mineralisation have undergone some marginal alteration and metamorphism, with primary igneous plagioclase, hornblende and pyroxene being altered to garnet (described as "uralitisation" by Edwards, 1954 and Stillwell & Edwards, 1956). This is particularly evident where ductile deformation (with annealing in adjacent sulphides) has affected the dolerite dykes in the North and BHP mines. Plagioclase laths were altered to manganiferous garnet in the immediate

contact regions, as were hornblende crystals. Some patches of sphene were developed along the margins of garnet-quartz veins (Stillwell and Edwards, 1956; Baker, 1958 and Ross, 1971). Minor sulphides were deposited along dyke margins and penetrated along cleavage planes and crystal boundaries; particularly pyrrhotite, with some chalcopyrite, galena, marcasite and trace sphalerite. Pyrrhotite and chalcopyrite are moulded on garnet grains. Pyrite formed from the breakdown of marcasite and pyrrhotite (Baker 1958).

The metasomatism, alteration and sulphide impregnation that affected dolerite dykes can be correlated with the widespread hydrothermal activity observed in Delamerian faults within the mineralisation (Webster 1993, 1994a, 1996a & b). Such activity can also be correlated with the development of galena-siderite-quartz veins within the main deposit area, such as the Consols Lode and the Consols Type vein and related structures described in the British Mine by Lawrence (1968a) and Boots (1972). These structures in turn were compared to the Thackaringa Style Veins by these authors. The alteration in faults within mineralisation is discussed further below.

The deformation and alteration of dolerite dykes (e.g. Stillwell & Edwards, 1956) is a relatively high temperature event and is here equated with the hydrothermal activity that took place in the British Fault and reactivated Lords Hill Fault, which generated the galena-siderite veins and open space pyroxene and pyroxenoids mineralogy seen in several localities.

#### **5.7.7. D4A Hydrothermal Activity and the Quartz-Siderite-Galena Veins.**

D4A faults were the loci for widespread hydrothermal activity in the mineralisation and in some nearby wall rocks (e.g. the Central Fault and the British Fault Zone). Localised hydrothermal activity took place along faults and produced high temperature minerals such as rhodocrosite in laminated and quartz-veined faults. Siliceous wallrock alteration at vein and fault margins (bleaching) developed in some areas (e.g. in rhodonite in 2L and in the amphibolite adjacent to the Consols Lode) and sturtite alteration formed within manganese silicates (Webster 1993, 1994a). Local, unusual occurrences of bustamite, hedenbergite and rhodonite were also formed.

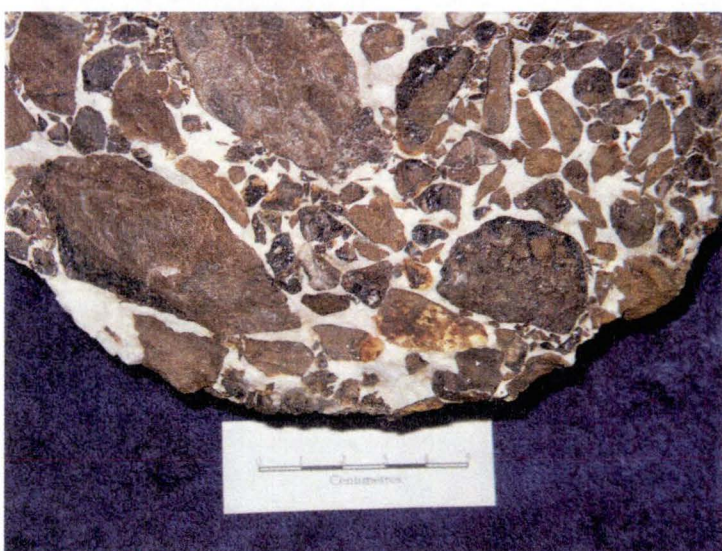
D4A produced brittle, hydrothermally altered manganocalcite-sturtite-(rhodocrosite)-inesite bearing laminated fault and vein systems (e.g. Figures 5.30b & c) and localised

brecciation (Figure 5.31) in all parts of the deposit but which were best developed in the Pasmaico Mine (Webster 1993, 1994a), within the Central Fault and the Flat Faults. Comparable structures in the northeastern end of the deposit include the reactivated Lords Hill Fault.

In the British Mine, hydrothermal activity along the British Fault Zone was associated with the formation of siderite-galena veins, which were correlated with the major development of similar argentiferous siderite vein ore in the ABH Consols Mine (Lawrence, 1968a; Boots, 1975). Kenny (1922) defined the Consols Lode as a Thackaringa Type vein, that is, one of a specific type of late epithermal silver-bearing siderite-quartz veins that most commonly occur in the Thackaringa mines to the west of Broken Hill. There are two main types of Thackaringa Type veins; silver-bearing veins and copper-bearing veins (Barnes 1988).

Thackaringa Type veins are rare in the immediate Broken Hill area and the two occurrences known are associated with the British Fault system. They are the small veins identified by Lawrence (1968a) on the 1200 Level of the British Mine and the ABH Consols Lode (the largest and richest Thackaringa Type vein known), developed within the nearby Consols Amphibolite (see below). In the mines area Lawrence (1968a) has traced cross-cutting galena-siderite-quartz veins of very similar type to the Thackaringa veins through 2L and 3L in the Browne Shaft workings. He has suggested that this vein is the continuation of the ABH Consols vein that lies within the amphibolite to the southeast of the mines area (this is not considered possible). He shows that this vein is of the Consols Type (a sub-group of the Thackaringa Type) and demonstrates that it is a fissure fill, which crosscuts quartz-chlorite-muscovite schist associated with the British Fault Zone. His mapping also shows that the vein cross cuts the strongly developed D3A fabric of the Thomson Shear and which is preserved by the orebody geometry. The mineralogy of the schist can be interpreted to be of D3B origin and the mapping confirms that the vein crosscuts a D3A fabric (see map BRIT1200 in Appendix 1), therefore, this vein clearly post-dates D3A, and almost definitely post-dates D3B. This example shows the relationship between a D4A vein-style quartz-siderite-galena vein and the established post-Olarian geometry of the Broken Hill orebodies. The vein probably formed during the reactivation of the British Fault Zone during the Delamerian Orogeny and has the same approximate strike as this D3A/B structure because of this fact.





**Figure 5.31.** BHF 7. Hand specimen of D4A fault zone matrix supported breccia within rhodonite-rich mineralisation. Clasts comprise variably altered rhodonite fragments. Many of the larger fragments preserve an early breccia texture. Fragments are variably altered around the margins and along fractures to dark brown to black resinous 'sturtite' (hydrous manganese silicate). The matrix comprises coarse-grained white calcite. Sulphides are a minor component, mainly being present as several small clasts of coarse-grained sphalerite. Fragments of clear vein quartz and sub-centimetre patches of late stage pyrite are also present. From the Central Fault in the NBHC area of the Pasminco Mine.

*b.* close-up view of *a.*

Several lines of evidence suggest that the Thackaringa Type veins in the British Fault Zone and the more widespread manganocalcite veins are genetically related and were formed during the same widespread D4 hydrothermal event. This evidence includes:

- The manganocalcite filled faults; veins and hydraulic breccias (Figures 5.30 & 5.31) that are common in the Central and Flat faults preserve evidence of significant fluid activity, as do the Thackaringa Type veins.
- The ABH Consols Lode and the cross-cutting galena-siderite veins in the lower levels of Browne Shaft cross cut the D3A fabric of the orebody and so must post-date it, fault veins and breccias do the same,
- The Thackaringa Type veins have not been deformed by F4 folds but are affected by D3B brittle faults (see below), as are fault veins and breccias,
- Crustiform textures and vugs indicate relatively low temperature and pressure of formation in both Thackaringa veins and other fault infill veins and breccias,
- Hydrothermally altered rocks have a characteristic pale fawn colour as opposed to the normal metasediments (Barnes, 1988), and
- Manganiferous, silicified alteration halos are commonly observed around D3A fault-vein systems in the orebodies and in the Consols Amphibolite on the walls of the Consols Lode.

Thackaringa Type veins are spatially associated with D3A-style shears and occur within retrograde, micaceous, chloritic or graphitic schists, or in strongly retrogressed metasediments which are hydrothermally altered. The veins post-date the retrograde S3 schistosity because they produce hydrothermal alteration within the wallrock schists along vein margins. This alteration consists of extensive sericitisation of feldspars, sillimanite and coarser-grained micas (Barnes, 1988). An example is the pegmatite adjacent to the Umberumberka Mine, which has been altered to a medium to coarse-grained, pale limey-green sericite rock containing scattered quartz granules (Barnes, 1988). Alteration is variable, ranging from affecting all rock types to centimetre-scale zones adjacent to the veins.

The alteration observed adjacent to Thackaringa Type veins is very similar to the extensive alteration associated with late stage quartz-muscovite-chlorite veins which are commonly found cutting retrograde schists in the mines area (e.g. Section 340). This alteration is also similar to the rhodocrosite-bearing, laminated vein systems and wall rock alteration observed within the D3A component of the Central Fault, Flat Fault (2L) and as isolated veined faults in the North Mine. D4A hydrothermal

processes associated with faulting probably also produced the garnet alteration within dolerite dykes in mineralisation (e.g. Baker, 1958)

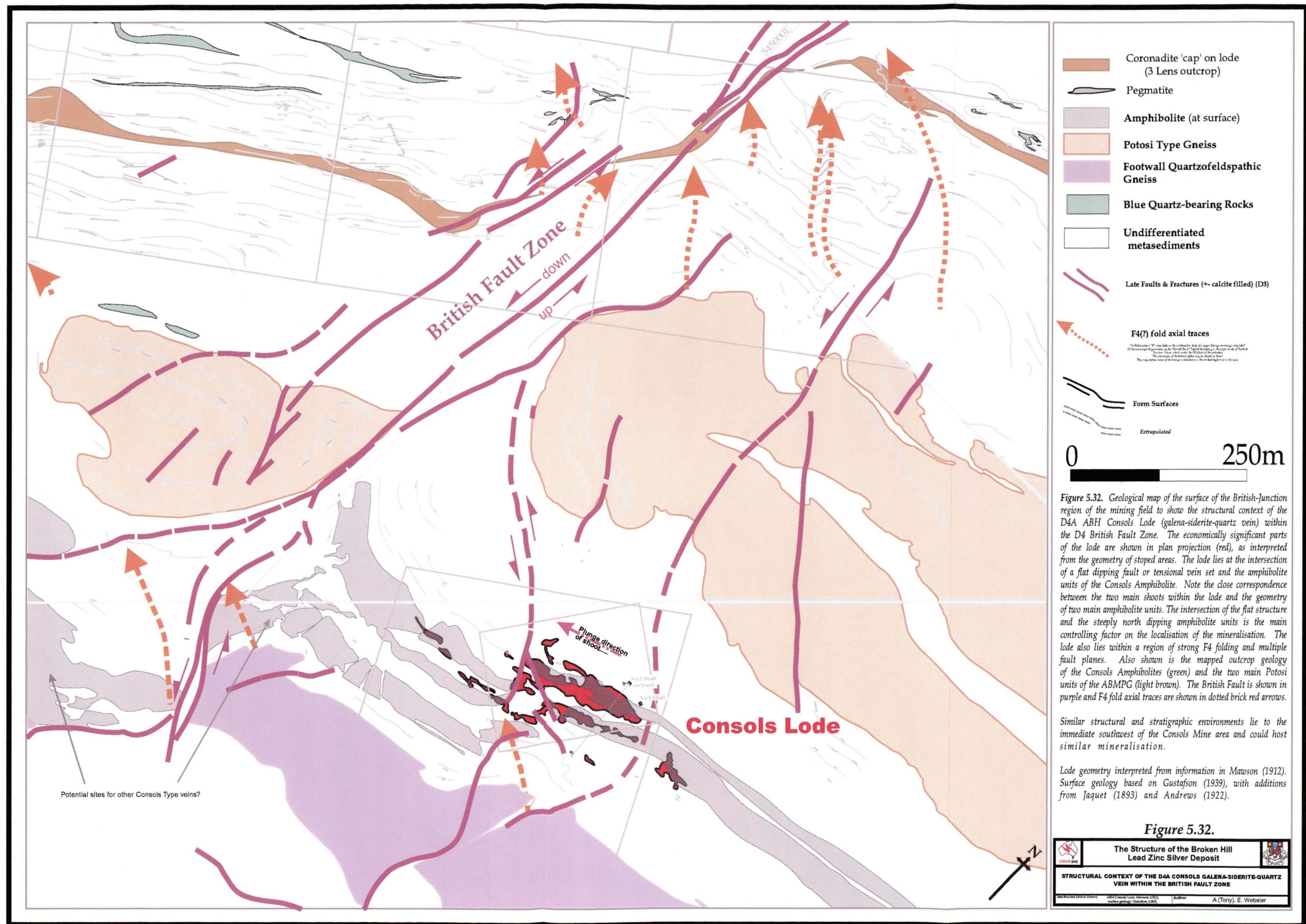
#### 5.7.7.1. *The ABH Consols Lode.*

The Australian Broken Hill Consols Ltd (ABH Consols) mined the bonanza grade “Consols Lode” silver vein between 1890 and 1903 (King, 1953). The Consols Lode is hosted within the Consols Amphibolite and lies to the southeast of the British-Junction region of the BH mining field (Figure 5.32). It is the largest “Thackaringa Type” orebody in the southeastern Broken Hill Domain and is the only mineralisation of this style that has produced significant ore in the Broken Hill area (Burton, 1994). Vein-style ‘lodes’ of Thackaringa Type are rare in the Broken Hill mining field and only one other significant (sub-economic) occurrence has been described. This is a set of galena-siderite veins described by Lawrence (1968a) (see above).

The Consols Lode is highly enriched in silver and contains a suite of minerals that are quite unusual for the Broken Hill area. The most common primary ore minerals are tetrahedrite, dyscrasite and allargentum and the most common primary gangue minerals are calcite, siderite and quartz (Burton, 1994). The unusual mineral complement and extreme silver enrichment of this orebody have made it the subject of mineralogical interest since its discovery. The present research provides additional information about the structural and stratigraphic context of this strange, silver-rich style of D4A mineralisation and augments what is already known (e.g. King 1953; Barnes, 1988; Burton, 1994).

The Consols Lode is hosted within a flat south dipping ( $20^{\circ}$  to  $60^{\circ}$ ; King, 1953), planar fracture, fracture system, or tensional vein set that intersects the steeply dipping amphibolite units in the Consols Amphibolite. The orebody consists of three main shoots, each developed at the intersection of the fractures and one of the three main amphibolite units. In effect, the Consols Lode comprises three lodes, a northern, middle and southern lode. The northern and middle lodes are joined at the eastern end. The southern lode appears to have been quite patchy and only mined at irregular intervals along the strike of the southern amphibolite (Figure 5.32). The lodes plunge to the southwest, parallel to the strike of the Consols Amphibolite and following the lineation defined by the intersection of the fracture system and the amphibolite units (Figure 5.33).





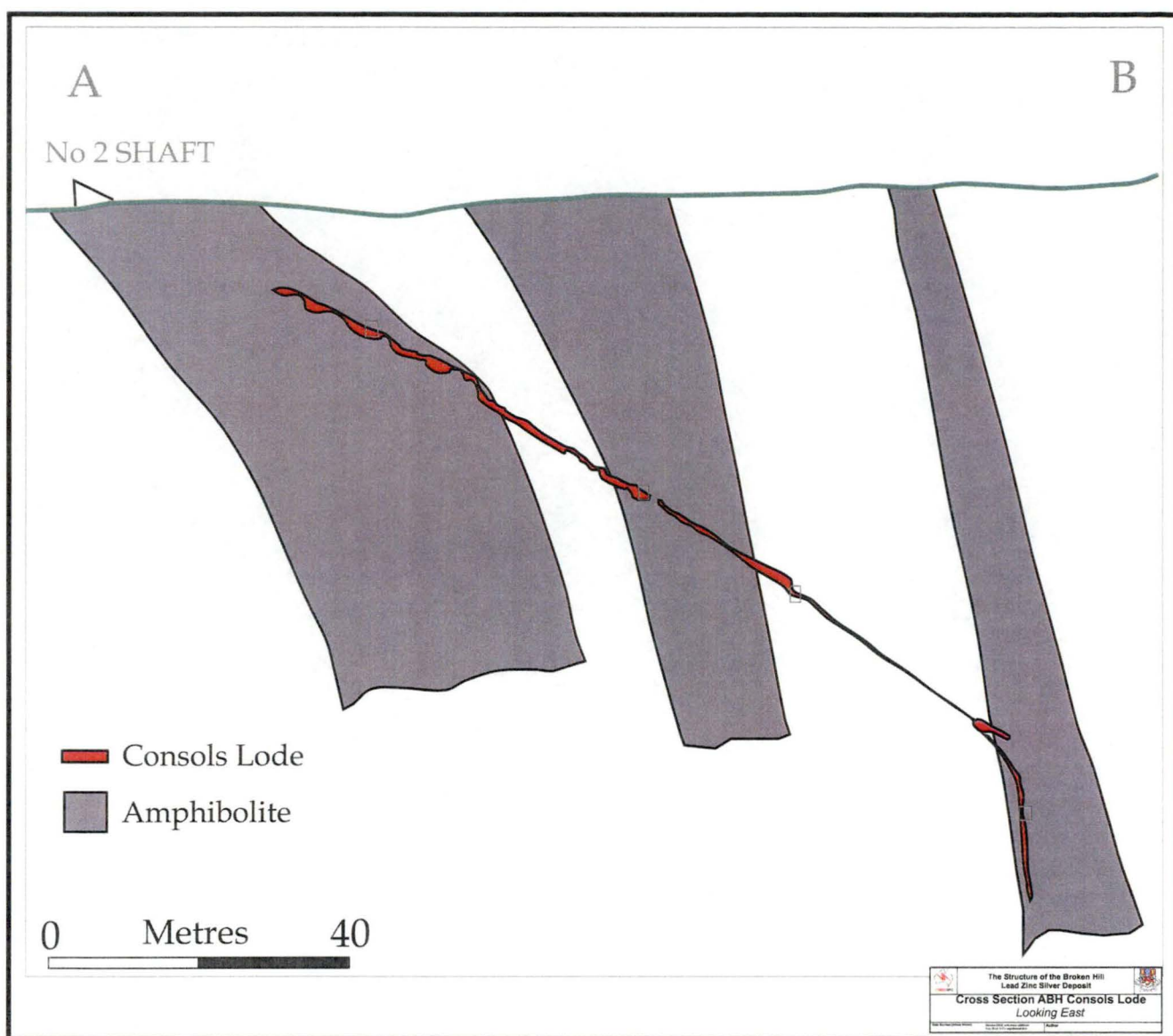


The Consols Lode occurs within the most complex zone of D4A deformation on the BH mining field. It lies within a broad and diffuse belt of F4 folding that is associated with a multi-planed fault system and brittle ductile deformation. The D3A Olarian structural trends produced by the Thomson Shear and preserved in the orebodies are extensively deformed by D4 structures in this region of the MinSeq. The Consols Amphibolite is more deformed by D4 in the area of the Consols Lode than it is anywhere else on the field. Gentle, open F4 folds and asymmetrically displaced blocks of amphibolite are common features of the Consols Amphibolite where it is intersected by the British Fault Zone (Figure 5.32).

The richest ore in the Consols Lode occurred at the intersection of the flat dipping fracture system and two steeply dipping "cross" veins (King, 1953). The main northern shoot occurs at the intersection of the "cross" veins and a point where the two northern amphibolite units merge, or are at least juxtaposed by deformation. The mapping of Gustafson (1939) may actually show the surface expression of the two "cross" veins, which are probably splays off the main British Fault Zone (see Figure 5.32). The western end of the main ore development in the ABH Consols Mine is probably terminated against the down-dip projection of the faults that Gustafson (1939) mapped at surface. Most of the mined part of the lode lies to the east of the two faults mapped at surface by Gustafson (1939).

The Consols Lode occurs within the most intense zone of D4A folding and fault development in the Broken Hill area. The amphibolite units that host the mineralisation are asymmetrically folded and the geometry of the folded units mapped at surface is mirrored in the shape of the lode at depth (Figure 5.32). The lode is a style of mineralisation that crosscuts all of the pre-existing (D1 to D3) structural fabric of the mining field. Amphibolite at the margin of the veins is bleached to a pale grey to "fawn" colour (authors observation in mine dump material), apparently by carbonate alteration (Barnes, 1988). The mineralisation exhibits 'cockscomb' textures, and other features that show that it was formed as fracture fill, relatively late in the geological history of the Broken Hill mining field.

The evidence available suggests that the Consols Lode formed within a broad zone of intense brittle-ductile deformation (the British Fault Zone), at the intersection between two or more fault splays and the amphibolite units of the Consols Amphibolite. The flat dipping lode may represent a hydrothermally active fracture system that



**Figure 5.33.** Cross section of the ABH Consols galena-siderite-quartz vein, looking east. Silver-rich sideritic mineralisation was developed at the intersection of a flat-dipping D4A fracture system and the steeply dipping amphibolite units of the Consols Amphibolites. Shoots of ore followed the intersection point of fractures and amphibolite. Section is looking east. The plane of the section is marked in Figure 5.22. Modified after Mawson (1912), with minor additions from Block 14 Co Ltd unpublished data.

transected the amphibolite, which then formed geochemical sinks for mineralising fluids. Alternatively, tensional veins may have developed in each individual amphibolite, as they were folded and contorted during D4A, and were 'fed' by the main fluid plumbing system. Whatever mechanism produced the flat dipping lode, it is clear is that the amphibolite units are the controlling factor in the deposition of the ore.

There seems little evidence available to show that the British Fault provided an adequate plumbing system for the movement of metals from the main orebodies to the site of the Consols Lode.

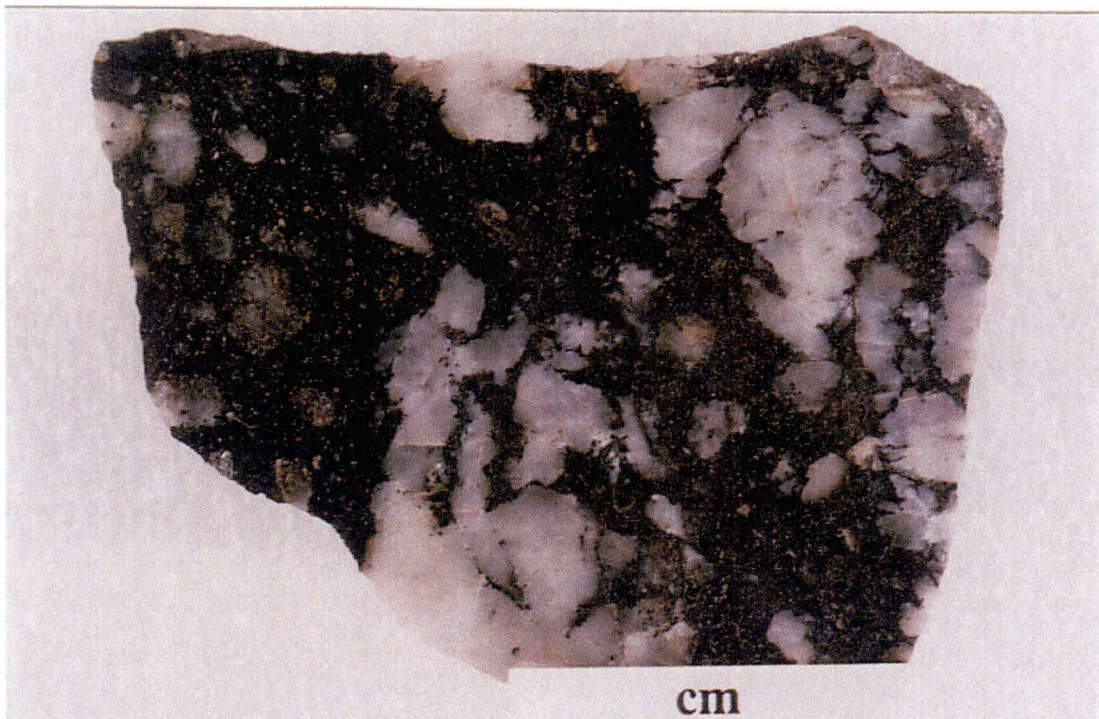
#### **5.7.8. D4B Brittle Faulting.**

D4B faults are characterised by very low temperature mineral assemblages such as chlorite, secondary calcite and pyrite. These constituents line faults and joints, infill vughs and cavities and cement milled and puggy fault products. D4B structures typically deform D4A features (such as laminated veins and calcitic breccias) and represent the final stages of D4 within the orebodies (Figure 5.34).

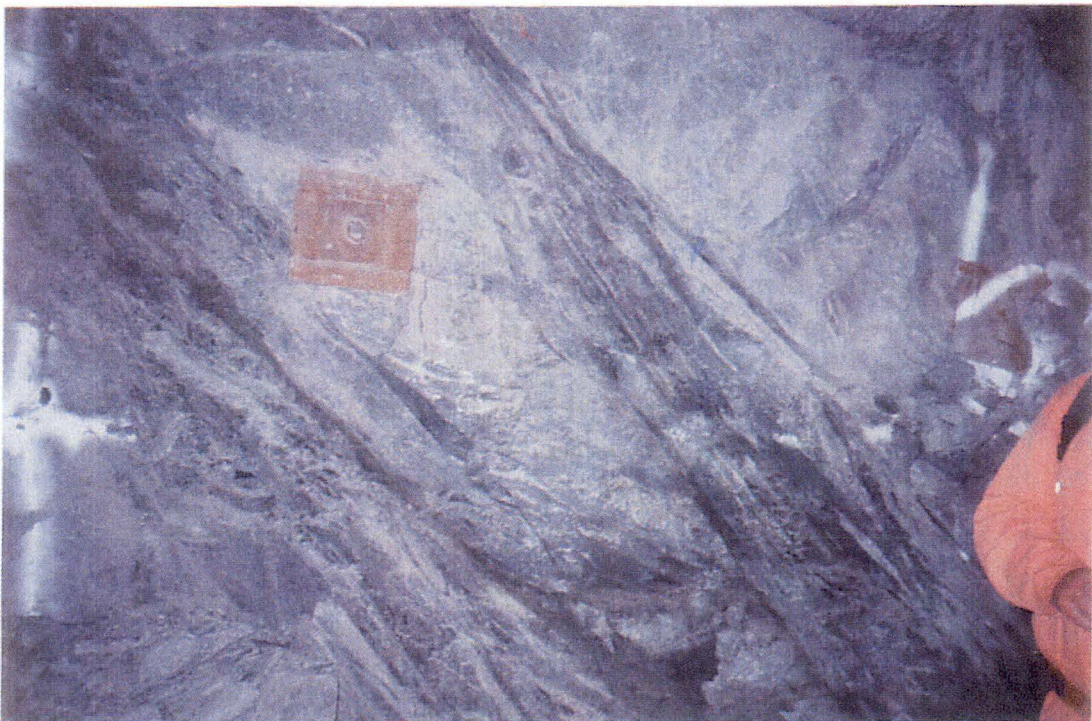
D4B occurred late in D4, resulting in the development of brittle, puggy and chloritic faulting (usually within pre-existing D4A and D3 structures). Mobilised pyrrhotite deposited during D4A was broken down to pyrite within chloritic faults and within mineralisation affected by D4B faults. There was also widespread deposition of secondary calcite within vughs ('dogtooth' calcite) and as cementing material in puggy and milled mineralisation and wall rocks. Some lead carbonates were formed in vughs and fracture planes. Pyrite was deposited on chloritic fault planes and there was widespread development of chlorite and pug on faults and joints.

Apart from diffuse joint sets, the specific effects of D3 were limited within the Garnet Quartzite Horizon (GQH). In ALL there was some hydrothermal alteration associated with the D4A Central Fault. A massive 'pug' zone comprising milled and fragmented garnet quartzite and metasediments, with some ore, was developed in the Central Fault on the 'overwall' of 1LU between the 19 and 20 Levels of the Pasminco Mine (Figure 4.36a). The Flat Fault passed through the down-dip extension of the 1LL orebodies where they were incorporated within the keel of the NBHC Synform, between the 21 and 22 Levels of the NBHC area of the Pasminco Mine.





**Figure 5.34a.** Polished slab of sulphide-quartz veining that has been deformed during D3B. Galena has deformed in a ductile manner ('schistose galena') and wraps clasts of fragmented white quartz veining. Fine-grained muscovite occurs along hairline fractures and in cleavage planes in the deformed vein quartz. North Mine, locality unknown but probably from the Fitzpatrick area in the vicinity of the Globe-Vauxhall Shear.



**5.34b.** Photograph of underground exposure of a typical D4B Fault plane developed within clastic metasediments, Pasminco Mine. Fault planes are generally chloritic and slickensided, and can contain milled and brecciated metasediments in zones of intense strain. Such faults are frequently developed in D4A structures where calcite-quartz veining, breccias and wall rock alteration have occurred. These earlier fabrics are often cataclased by the D4B phase.

Widespread muscovite and chlorite alteration, jointing and fracturing was formed throughout the GQH during D4B. Jointing is commonly observed along lithological contacts (especially garnet quartzite and clastic metasediment contacts) and pre-existing shear fabrics.

#### 5.7.8.1. *Central Fault & Flat Faults.*

The Central Fault is a prominent D4 fault zone that is significant in the Pasminco Mine and the name derives from common usage by the mining geologists. The Central Fault dips at approximately 60 degrees northwest, and has a strike that is approximately parallel to the long axis of 2L (see Figure 4.35 & 4.36) and only negligible displacement. It cuts the centre of 2L between the 19 and 21 levels as a series of veined brittle fault planes, veins sets containing manganoan calcite, rhodocrosite and inesite; and later stage pug zones, vughs, cavities and cataclasite zones that often contain 'dogs tooth' calcite (Webster 1994a; 2000b; this study).

The Central Fault belongs to the latest generation of deformation to affect the mine area. However it does have many features which suggest that it was initiated at lower amphibolite facies (D3B), including an intensely schistose quartz-muscovite-biotite fabric in metasediments below 2L. It has at least two phases of development history; an early phase associated with relatively high temperature hydrothermal activity and a later brittle, chlorite-generating phase (Webster, 1994a).

The Central and Flat Faults have no apparent relationship to any pre-existing structural fabric in the orebodies, such as a D3A shear planes, and both dissect all pre-existing lithological and structural features, including 2L. They are the only generation of structures to do this and as a result are particularly important in underground mining operations because of the poor ground conditions they cause.

The Flat Fault is a northwest striking; shallowly south dipping (15-20 degrees) fault plans that cuts the east limb of the 2L between the 16 and 24 Levels of the Pasminco Mine. The name is derived from common mine usage. It mostly contains chloritic and puggy milled material in metasediments but can be veined where it transects 2L (Webster, 1994a).

## 5.8. DISCUSSION.

### 5.8.1. Summary of the Structural History of the Broken Hill Mineralised System.

The Broken Hill orebodies and their wall rocks have been affected by two major periods of regional metamorphism (M1 and M2), both of which coincided with protracted deformational events (D1, D2, D3 and the later D4). The characteristics of the deformational events are summarised in Figure 5.35.

There is evidence preserved in the mineralised system for only a single protracted high grade, granulite to upper amphibolite grade metamorphic event (M1). M1 is correlated with the second metamorphic event of Laing et al. (1978). A single protracted deformation affected the rocks of the Broken Hill mining field during M1 and had three distinct phases; D2, D3A and D3B, commencing at or immediately prior to the peak of metamorphism. Each event took place as M1 waxed and waned, with D2 taking place at the culmination of the event and D3 as it waned. Most deformation of the mineralised system took place during D2 and D3A. An earlier D1 event produced no recognisable macroscopic structures in the mining field area. It is only represented in the MinSeq by a pervasive S1 schistosity and by pegmatite dykes. It is uncertain if D1 took place during M1, or whether it represents an earlier phase of regional metamorphism.

There is continuity from D2 folding to early retrograde D3A ductile shearing and attenuation (relatively high grade), to D3B quartz-muscovite biotite shearing. Each successive stage of D3 is characterised by progressively lower grade metamorphic mineral assemblages (summarised in Figure 5.36) and styles of deformation reflecting decreasing ductility. The style of deformation is interpreted to reflect a stage in the waning of M1 regional metamorphism.

High grade, south verging, asymmetric F2 folding within the mining field is correlated with the F2 of Laing et al (1978) and is the cause of much of the present orebody geometry. F2 in 3L in the North Mine area was associated with a pervasive galena-defined S2 axial plane foliation, within which rhodonite and spessartine garnet was recrystallised in the sulphide matrix, and folding and transposition equally affected both ore and adjoining wall rocks. An S0 layered distribution of several gangue



D1 (OLARIAN OROGENY)	D2 (OLARIAN OROGENY)	D3A (OLARIAN OROGENY)	D3B (OLARIAN OROGENY)	D4A (DELAMERIAN OROGENY)	D4B (DELAMERIAN OROGENY)
Pegmatite intrudes Lode Sequence:	Asymmetric south verging folds in orebodies.	High grade sinistral shearing, minor F3 folds.	Quartz-muscovite- biotite shear zones.	Brittle fault systems & local refolding	Late-stage faulting, joint & fracture systems
Separation pegmatite, southwest end,	Transect the orebodies at c20° to their original strike.	Belt of Attenuation B Lode Shear & Thomson Shear develop	Early biotite-rich phase	Displacement of Northeast region by British Fault System NE block up & offset to north by British Fault Zone - approx' 500-750m. Offset of D3A Thompson Shear in Browne Shaft Area	Chloritic, brittle & puggy stage of movement on D4 faults
Widespread stratiform dykes at margins of psammite & quartzofeldspathic units in the northern leaves	Second order F2 folds: SXS, ZCA, NBHCS SMA, CMA, CMS, BHPS, B14A, BA, BS, NMA, WKS etc	250-300m sinistral movement, west block up (reversed)	Formation of all of the significant retrograde shears of the mining field area including Later Globe Vauxhall & Western Shears, Central Shear, Early DeBavay Shear Willa Willyong Shear	DeBavay Fault Zone	Reactivation or continuation of D4A
Pegmatite intrudes 2 Lenses.	Isoclinal style in the NE & central mining field, tight folds in SW.	Attenuation of F2 folded geometry of 2L, 3L, 1LL, 1LU (Belt of Attenuation) 250m sinistral, west block up displacement of 3L & 2L in the Browne Shaft area (British Shear)	Final stages of B Lode Shear development	Brittle faulting throughout the mining field	Chloritic, puggy & muscovite altered fracture planes, with deformation of D4A features
Banding in lode pegmatite?	Formation of the initiation points of 'droppers' (small scale F2 synformal folds)	GQH dissected by BL Dropper Shear & related structures	Completion of shear offset of 2L & 3L in the North Mine area (Fitzpatrick Orebody)	Hydrothermal activity along faults produces laminated veins & carbonate alteration of rhodonite-bustamite near fault systems	Chloritic faults, shears, pug zones & milled ore.
Biotite-sillimanite foliation (S1), parallel to bedding in MinSeq metasediments	S2 axial plane foliation defined by galena distribution in 3L in North Mine	Development of 'Axial Plane Orebodies' in B Lode Shear	Completion of the attenuation of 2L & 3L between the 29 & the 32 Levels of North Mine	Formation of ABH Consols siderite- galena-silver vein at intersection of D3B British Fault splay & amphibolite units.	Secondary calcite lining vughs & cementing fragments.
Isochemical metamorphism, annealing & grainsize coarsening in orebody sulphides & gangue. S0 mineralogical variations coarsened & exaggerated	First order F2. HWS, IRS, MBA, Broken Hill 'Synform' ('Airport Antiform') etc	'Droppers' form in shear planes & attenuated regions of southwest region (particularly Main Shear).	Muscovite alteration of pegmatite dykes		Jointing & faulting throughout the deposit
Coarse knots & bundles of fibrolite developed in pelites in the NE region (wrap pyrite in places)	Grainsize coarsening of gangue & sulphide	Extreme shearing of Central Mine Synform by Central & Channel Shears results in 'dropper'-like shear hosted sheets of ore in lower levels of South, Central & BHP Mines	Lower amphibolite- greenschist grade	Galena-quartz-siderite vein in lower levels of British Mine	Pyrite along fault planes, vughs & joints
	Annealing crystallisation throughout orebodies	Minor F3 folds develop in shear zones. S3 sillimanite is characteristic		Rhodonite, bustamite, bannisterite, hedenbergite rhodocrosite form in cavities in some faults.	
	Extensive mechanical & fluid phase sulphide mobilisation in the orebodies. Includes fluid phase sulphide migration into rhodonite-bustamite margins & wall rocks (mostly garnet sandstone & garnet quartzite)	Attenuation of F2 folded geometry of 2L & 3L between 29 & 32 Levels in the North Mine. Shear offset of 3L & 2L between 32-34 Levels of North Mine (Fitzpatrick Orebody).		Gentle refolding of mining field on NW- SE axis F4 folds traverse mining field & refold F2 folds in MinSeq causing central plunge reversal (SW plunge at SW, NE plunge at NE end. Pegmatite veins develop in F4 hinges.	D4A: Locally lower amphibolite grade & possibly higher in hydrothermal systems?
	Wall rock silicification at orebody contacts (silica metasomatism), especially on margins of 3L in North Mine.	CL offset from BL by 250m sinistral north block up movement of BL Dropper Shear		Intrusion of fine- grained dolerite dykes into mineralisation along NW-SE planes Minor mechanical sulphide mobilisation. -Dolerite dykes dismembered.	D4B: Greenschist grade.
	Differentiation of sulphide constituents into Pb-Ag-Au-As- W(Cu) - rich fluid phase & Zn-Fe-Cu - rich fluid phase	Silica metasomatism of ore & wall rocks in sheared parts of the deposit (e.g. 1L & 2L in Pasmenco Mine)		Minor hydrothermal activity in ore. Garnet alteration & sulphide impregnation of dolerite fragments	
	Fracturing/brecciation in GQH. Quartz- hedenbergite veins & breccias, silicification, quartz veins & stockworks	Upper amphibolite- lower amphibolite grade.		Minor fluid phase sulphide mobilisation (pyrrhotite, chalcopyrite & minor galena mobilisation)	
	Especially developed in ALL & ALU, in the tight infolded F2 keel of the NBHCS.			White quartz veining; silicification of some pegmatite; wallrock bleaching, silicification, sericitisation & coarse muscovite	
	Beginning of silicification & alteration of pegmatite				
	Initiation of BLShear & related structures?				
	Granulite-upper amphibolite grade				

**Figure 5.35.** Summary of the main structural events that have affected the Broken Hill mineralised system & Mine Sequence.

species within the ore retained much of its original distribution in the folded orebody. F2 folds also deform a well-defined stratification in 2L, BL and ALL. Coarsely crystalline, calc-silicate-bearing zones form margins on masses of rhodonite dismembered during D2, in 2L in the Pasminco Mine (Webster, 1994a). Lode pegmatites in the mineralisation are also folded and are often penetrated by garnet-quartz-sulphide veins, calc-silicate alteration (wollastonite?) and silicification. Pegmatite dykes are strongly altered by syn-D2 to syn-D3 siliceous metasomatism and sulphide mobilisation.

There is not a single pair of folds controlling the geometry of the ore lenses and extending the entire length of the deposit, as has been suggested by previous workers (e.g. Gustafson et al, 1950; Laing et al., 1978). There is actually a series of asymmetric F2 folds. The orebodies do not plunge parallel to the axes of high-grade F2 folds, nor do they plunge parallel to any other generation of folding. Orebodies and enclosing lode rocks traverse F2 fold hinges and plunge both northeast and southwest throughout the deposit as a result of F4 refolding.

All significant fluid phase sulphide mobilisation, and most mechanical sulphide mobilisation, took place within the orebodies during D2. S0 banding and syn-depositional stratigraphic variations within the orebodies (e.g. rhodonite horizons, calcite banding, the B Lode 'Complex' layering) are folded around F2 axes and modified by syn-D2 mobilised sulphides.

D3A high grade shearing (granulite to upper amphibolite grade) immediately followed F2 folding and extensively modified the folded geometry of the mineralised system. D3A shearing has preferentially affected F2 synforms containing large masses of clastic metasediment hosted ore. D3A shears contain localised occurrences of mesoscopic F3 folds with a well-defined sillimanite biotite S3 axial plane fabric, and planes of intense transposition.

D3B shearing, characterised by a lower amphibolite to greenschist grade mineralogy is recognised by the extensive belts of biotite-muscovite-quartz schist (shear zones). It developed over a protracted period. The effects of D3B are not evenly distributed in the mining field and it affected localised areas, particularly in the northeastern part of the deposit. D3B shears tend to be focussed in areas strongly deformed during D3A (Webster, 1993, 1994a)..

MINERAL	D1	D2	D3A	D3B	D4A	D4B	Comments
<i>Actinolite</i>			----	---			Hairline fracture fill
<i>Apatite (Fluorapatite)</i>	-----	-----	-----	-----	-----		D4A from Birch (1999)
<i>Biotite</i>	-----	-----	-----	-----	-----	---?---	
<i>Blue Quartz</i>	-----	-----	-----	-----			
<i>Bustamite</i>	-----	-----	-----		-----		Hairy & 'crustiform' in D4A large crystals in 2L in D3A & D2
<i>Calcite</i>	-----	-----	-----	-----	--2---	--2---	
<i>Chalcopyrite</i>	-----	-----	-----	-----	-----		Mainly as veins
<i>Chlorite</i>						-----	
<i>Cummingtonite</i>			----	---			With saccharoidal quartz.
<i>Feldspar</i>	-----	-----			-----		D4A fault, Nth Mine (Birch, 1999). Mostly in pegmatite in ore
<i>Fluorite</i>	-----	-----	-----	-----	--2---		Crystals in D4A Faults
<i>Galena</i>	-----	-----	-----	-----	-----	--2---	
<i>Garnet</i>	-----	-----	-----	-----	-----		
<i>Hedenbergite</i>		-----	-----		-----		In D4A faults with bustamite, D2 / D3A quartz veins & sheared 2L.
<i>Inesite</i>					-----		
<i>Knebelite</i>		-----	---				Margins of rhodonite masses
<i>Loellingite / arsenopyrite</i>			---	-----			Veins & matrix in garnet SS. Some patches in remobilised sulphides.
<i>Manganocalcite</i>					-----		
<i>Muscovite</i>				-----	-----	-----	
<i>Pyrite</i>						-----	
<i>Pyrrhotite</i>	-----	-----	-----	-----	-----		Pyrrhotite precursor pre-D1
<i>Quartz</i>	-----	-----	-----	-----	--2---		
<i>Quartz Blue Vein</i>		-----	-----				
<i>Quartz White Vein</i>			-----	-----	-----		
<i>Rhodonite</i>	-----	-----			-----		In some D4A faults (Birch, 1999).
<i>Rhodocrosite</i>					-----		
<i>Siderite</i>					-----		D4A faults.
<i>Sillimanite</i>	-----	-----	-----				
<i>Sphalerite</i>	-----	-----	-----		-----		Sheared during D3B (augen)
<i>Sturtite</i>					-----		
<i>Tetrahedrite</i>	-----	-----	-----				
<i>Wollastonite</i>	----	-----	-----				

----2---- = secondary phase

**Figure 5.36.** This data is based on field observation and only major phases are listed. Relationships are also based on field observations. Some data from Webster (1994a) and information on additional localities of some species is from Birch (1999). A mineral is listed as a phase if it recrystallised during an event.



A second period of metamorphism (M2) affected the orebodies during the Delamerian Orogeny (Stevens, 1986) and locally exceeded greenschist grade. M2 was associated with a fourth period of deformation (D4) and some igneous activity. Within the orebodies, it caused the re-activation of Olarian D3A-D3B shears, forming a generation of brittle faults. Some hydrothermal activity along D4 faults produced alteration within mineralisation. Some mechanical sulphide mobilisation dismembered dolerite dykes within 2L and 3L and minor fluid-phase sulphide mobilisation impregnated the margins of the dykes. D4 developed much later than the Olarian Orogeny. D4 had particularly widespread effects in the northeastern part of the mines area, being mainly manifested as brittle-ductile to brittle deformation that is most commonly represented by the development of the extensive fault, joint and fracture systems.

There were at least two distinct phases in D4, an earlier, relatively high-grade phase that possibly reached lower amphibolite grade in places and with locally higher grades in faults associated with hydrothermal activity (D4A) and a successive D4B phase, which was possibly a distinct reactivation event. D4A was associated with localised ductile deformation, in the form of F4 folds, and caused the major reversal in F2 plunges in the central mining field (Webster, 1996b, this study).

Further summary comments are presented in Chapter 7.

### **5.8.2. Variation in the Effects of Deformational Events.**

The present investigation has shown that each of the three most significant deformations that have affected the Broken Hill mining field (D2-D4) have varied in their effects in different regions of the deposit. One particular event may predominate in a relatively localised region of the mining field but be weakly developed in another. For example, a domain may preserve a predominance of F2 fold geometry, while an adjacent domain may be dominated by an early retrograde S3 shear fabric. The effect of the same event may also be variable, as is shown by the greater intensity and more complex style of folding in the northeastern region of the mining field compared to the southwestern end.

Webster (1994a) recognised that lithology could be an important influence on the effects of a particular deformation, and impact on the style and manifestation of particular events. This observation has been confirmed by the present study. For

example, the contrasting competency of the rock types forming the MinSeq have been a major influence on the location of, and degree to which D3 shears have developed in the mines area. The most important of these rock types has been the garnet quartzite comprising the greater part of the Garnet Quartzite Horizon and the sulphide-silicate-calcite rocks of 2L, 1L(upper & lower) and 3L. Webster (1994a) recognised that D3 shearing was mostly focussed in the clastic metasediments of the MinSeq, particularly those hosting these ore lenses.

The D2 fold geometry of the GQH, 3L and 2L was a major factor in the locations in which later shears formed. Arch and trough shaped masses of competent rocks in fold hinges tended to preserve folds, while less competent rock types on the flanks and in fold limbs were preferentially sheared. D3A attenuation has been preferentially focussed within second order F2 synforms in which large masses of 2L and 3L ore are hosted. This type of sheared fold keel forms a major component of D3A shearing throughout the entire deposit and shearing that is focussed in such structures propagates into the surrounding MinSeq (e.g. see maps NBNH20, & STH1070 in Appendix 1). Other competent rock masses also influenced the location of the formation of D3A, including the Footwall Quartzofeldspathic Gneiss (see Figure 5.6 and 5.7), Potosi type gneiss units and amphibolite (Webster 1994a).

Elements of the MinSeq that are dominated by particular lithologies (such as the GQH) influence the style and intensity of many structures. The following sections discuss some of the variations in the effects of the D2 and D3 on the orebodies and elements of the Lode Sequence.

### **5.8.3. Structure of the Garnet Quartzite Horizon.**

Perhaps the most structurally distinctive unit within the Mine Sequence is the Garnet Quartzite Horizon (GQH). The Garnet Quartzite Horizon represents a part of the Lode Sequence in which D2 folding and D3 shearing have been less pervasive in their effects on the orebodies than they were in the clastic metasediment-dominated part of the upper Footwall Succession. F2 folds are well preserved in the zone. Characteristic structural features of the GQH are: better preservation of F2 fold geometries, 'brittle' shearing and large zones of brecciation in which silicification, sulphide mobilisation and calc-silicate formation has taken place as a result of syntectonic metasomatism.

The structural dislocations that were produced during D3, and the variable intensity of this event throughout the Pasminco Mine, resulted in the formation of two distinct structural sub-zones within the GQH. The two sub-zones are structurally distinct and are defined as the southern domain and the northern domain. They are separated by planes of D3A dislocation known as the B Lode Shear and the Western Zone of Shearing focussed around the hinge of the F2 ZC Antiform and its common limb with the NBHC Synform (see maps NBH14 to NBH19 in Appendix 1).

In the ZC-NBHC area of the Pasminco Mine, the southern domain is typified by strongly attenuated, very tight to isoclinal F2 folds and contains much of ALL, all of ALU, 1LL, 1LU, 2L and 3L. ALU, 1LL and 1LU are mostly contained within the highly attenuated keel of the NBHC Synform, while 2L and 3L occupy both the NBHC Synform and ZC Antiform. In the Southern Cross area of the Pasminco Mine, the southern domain is much reduced in size but impacts on the Southern Cross Synform, which is dislocated and strongly attenuated. Dislocation is focussed along the southern margin of the GQH and is produced by the southwestern continuation of the merged WZS and Main Shear.

The northern domain contains B Lode, its satellite ore lenses and Western A Lode and is characterised by tight F2 folds at the northeastern end. Otherwise, the orebodies and the GQH retain a high degree of their original sheet-like form (S0). It is only affected by relatively minor D3A shearing, particularly that associated with the B Lode Shear.

The relationships between F2 and the primary geometry of the mineralisation is also observed in the GQH and B Lode Horizon, with mineralisation transgressing D2 fold axial surfaces in a similar manner to that observed in the 2L by Webster (1994a). In fact, the relationships between folds and stratigraphy are better preserved in the GQH than anywhere else on the field. 2L and 3L have been too heavily modified by shearing to provide definitive evidence of this relationship.

The original strike of 3L, 2L and the 1 Lens group is slightly different to the strike of the GQH hosted orebodies, trending slightly more northerly. This feature predates D2 folding and is probably a primary depositional feature. It results in 2L and its related orebodies gently diverging from the GQH and BLH to the northeast of the Pasminco Mine.

Many of the styles of mineralisation that were formed within and adjacent to the siliceous orebodies in the GQH during deformation are markedly different to those that were formed in 2L and 1LL. The styles of mobilised and metasomatically altered mineralisation that developed within the GQH were strongly influenced by the brittle way that the garnet quartzite deformed during folding and shearing. Brittle deformation, siliceous metasomatism and fluid-phase sulphide mobilisation were the processes that most influenced the ways in which the siliceous orebodies were affected by deformation. This differs from 2L, where the sulphide-carbonate-silicate mineralisation was the dominant influence on the way the deformation affected the orebodies.

Despite the apparent differences in structural style that are observed in the GQH, the same structural events have affected it as have affected 2L and 3L elsewhere on the field. All of the structural relationships between D2 and D3 structures that were identified in 2L by Webster (1994a), and recognised elsewhere in the field (this study) have been observed in the GQH and the orebodies it hosts.

The garnet quartzite largely remained competent, even at the peak of metamorphism (D2) while the clastic metasediments of the Lode Sequence (including ore) were ductile, and preferentially sheared. The garnet quartzite seems to have remained as competent masses. This results in F2 geometries that are better preserved by the GQH than they are within psammite / psammopelite and pelite (and mineralisation).

Brittle-ductile and brittle deformation took place within the GQH and was associated with extensive development of fluid-phase styles of mobilised sulphides and siliceous metasomatism, which formed sulphide-silica veining within the garnet quartzite. Within clastic metasediments, D2 was manifested as ductile folding and mechanical sulphide mobilisation. Fluid-phase mobilised sulphides penetrated into competent rocks within the orebodies (eg. massive rhodonite layers) and into the wall rocks adjacent to the orebodies (especially garnet quartzite). The abundant breccias and quartz-hedenbergite-garnet-sulphide vein systems and stockworks formed in the garnet quartzite support this view. It is probable that the GQH remained relatively competent during D2 and thereby influenced the style of D2 folding, and the positions in which the most intense planes of D3A attenuation developed. The garnet quartzite

has also preserved more of the original F2 fold geometry in some areas because of its greater rigidity during D3A attenuation.

The effects of D3A also differed within the GQH and the clastic metasediments. Brittle deformation initiated during D2 still predominated within the GQH but was localised into discrete shears (including droppers). Large infolded blocks of garnet quartzite within F2 hinges were dislocated and dissected by D3A shears and offset up to 300 metres. In the clastic metasediments, broad belts of ductile transposition and attenuation developed at major lithological contacts, at locations that were influenced by the folded geometry of stratigraphic units (especially 2L).

The hinge of the ZC Antiform is displaced to the southwest in a sinistral sense by D3A shearing. The northern limb of ALL (WAL) has been moved southwest and upwards relative to the southern side. Its orientation changes down plunge to the southwest from an original strike of approximately 245 degrees to a more southerly trend of 215 degrees. It is close to its original orientation on the 14 Level (plunging towards 245 degrees) but is completely rotated to lie at 215 degrees by the time the 18 Level is reached. On the 19 Level, the ZCA has passed away to the northwest of BL. On the 19 Level, the fold is a very broad open structure, which forms the arch-like 'plunge reversal' between 2L and the Southern Cross area. Shearing associated with the WZS parallels the stratigraphy in this area, particularly the limb of the GQH hosting WAL, where it lies within the long northern limb of the ZC Antiform. The extent and degree to which sinistral shearing has attenuated the hinge of the ZC Antiform is mirrored in the extent to which the southern margin of 2L has been sheared in a sinistral manner along its southern margin in the ZC area.

#### **5.8.4. The Structure of B Lode.**

B Lode (BL) consists of an elongate lenticular body of mineralisation (Figure 4.41) which has been relatively weakly effected by D2 folding. Throughout most of its strike extent, BL lies to the north of the major effects of D3 shearing and it lies outside the influence of the majority of F2 folding. Consequently, the orebody retains a large degree of its original ribbon-like form and the primary stratigraphy (see Chapter 4).

D2 folding only really affects BL at its northeast and southwest ends. In the NBHC area of the Pasminco Mine, the extreme northeastern end of BL becomes incorporated

into the structurally complex region of shearing and folding associated with the ZCA hinge and the B Lode Shear. In this area, shearing dislocated masses of ore and the weaker distal mineralisation in the hinge of the ZC Antiform. BL mineralisation was mobilised into the D3A B Lode Shear to form the 'Axial Plane Orebodies' (Stockfeld, 1993a & 1993d) and the northern peripheries of the B Lode Horizon and the Garnet Quartzite Horizon were displaced along this structure to the southwest (e.g. Figure 4.15b and see also maps NBH13 to NBH15 in Appendix 1). The displaced portion of the distal B Lode orebody is known as 'C Lode'.

In the Southern Cross area, the southwestern end of B Lode is weakly affected by open F2 folds (see map NBH18 in Appendix 1). The weak F2 folding in BL contrasts sharply with the tight folding and later shearing that has produced the present geometry of the nearby Southern Cross Synform (see maps NBH19 to NBH21 in Appendix 1).

#### **5.8.5. Northeastern Domain.**

F2 folding is markedly more complex, isoclinal and differentiated in a section of the mining field that extends from the BHP Mine, to at least the 32 Level of the North Mine. The complexity of the F2 folds becomes most marked from the north-eastern end of the Block 14 Mine and is particularly remarkable within North Mine, where it is associated with the intense crenulation of S0 layering and S1 (e.g. Figures 5.11, 5.12 and 5.16).

As described above, the distinction between D3A shearing and F2 folding is less obvious in this region than it is in the southwest. The whole package of clastic metasediments hosting 2L and 3L is intensely folded, crenulated and transposed, rather than exhibiting the clear division between F2 folds and discrete D3A shear planes. It is possible that this region of the mining field lies within the tightly folded limb of a major F2 antiform.

The northeastern region of the mining field is also distinctive in that there is a broad halo of siliceous blue quartz-garnet-sulphide alteration formed around 3L and between 3L and 2L. The alteration overprints bedding and the folded geometry of the metasediments and is interpreted here to be a syn-D2 tectonic alteration. The zone only seems to come into prominence in the upper levels of North Mine. While small



developments of similar blue quartz alteration are seen elsewhere on the field, the zone in the North Mine is by far the most significant and extensive.

The northeastern domain is punctuated by two major shear/fault systems; the British Fault Zone and the DeBavay Fault Zone, both of which may exploit pre-existing D3B shear zones. Both zones represent regions of intense D3A shearing and D4 faulting. The DeBavay Shear and Fault Zone has not been examined in any detail during this study. The multiple planes of the British Fault Zone formed after the reversed double plunge of the BH lode was established during F4 folding. This is shown by the two planar northeast plunging offsets seen in the British Orebody and King Shaft Orebody which retain a ghost of the original northeast plunge of the orebodies that was subsequently dislocated by the steeper D4A fault planes.

#### **5.8.6. Structure of the Broken Hill Mining Field – Is it Unique?**

Recent workers have suggested that the structural complexity of the Broken Hill mining field is somehow unique, compared with other regions of the Broken Hill Domain (e.g. White et. al., 1993; Rothery, 2001). The inference in these descriptions is that there is a greater structural complexity in the mining field, particularly in the effects of early shearing, which has had some type of profound effect in the genesis of the deposit, or on the subsequent history of the deposit. However, are such models merely the result of the variable data densities that are typical of any long-lived, prosperous and densely drilled mining field, such as Broken Hill, compared with its much more sparsely drilled 'hinterland'?

Underground workings and mined areas, such as the Broken Hill mining field, are geologically recorded in detail for a great many mining, exploration and resource definition reasons, while areas distal to the underground workings and densely drilled regions of the mineralised system are only known in less detail. Distal regions of the mineralised system, and the 'host stratigraphy', are often only known from drill hole intersections that are many hundreds of metres apart (even on the same cross sections). Drill hole intersections into key marker units may have deviated from the actual plane of the cross section and be hundreds of metres away, yet have to be used to interpret the stratigraphy on the section. Compilations of such variably oriented 'pinprick' data from drill holes tends to lead to a 'smoothing' of the interpretation by the exploration, resource definition and mining geologists. When a densely drilled and mined area is

added into such cross sections, it can give the impression of far greater structural and stratigraphic geometrical complexity in the mined area which is, by necessity, focussed around the orebodies. These sections often form the basis of subsequent research projects and regional data compilations.

If an area of unmineralised metasediments is mapped at the same scale as is typical on the mines (1:250 scale, 1:500 scale, 1:1500 scale), rather than the more typical regional scales (1:5000; 1:10000; 1:15000; 1:25000 etc.), then the same types of fold and shear relationships and styles are revealed. Recently, Stevens (1999) undertook detailed outcrop mapping in the Sundown Group in the "Monuments" area. The outcrops he mapped measured 1.5-12m<sup>2</sup> in area and comprised an unmineralised pelite-psammite sequence. The mapping scale he used closely approximates mine geological scales in use on the Broken Hill mines.

His work revealed comparable structures to those identified within the Broken Hill mineralised system during this study. Stevens' (1999) mapping showed that pelite units in this sequence preserve fold hinges with clear, well-preserved bedding and this defined rounded tight folds. However, significant dislocation was observed at fold margins, where high temperature, high strain zones (shears) dislocate the hinges. Psammite units were particularly susceptible to high strain and pegmatite formation.

Steven's (1999) mapping shows that comparable structural relationships exist in the unmineralised monotonous sequence of psammite and pelite in the Sundown Group as exists in the mineralised system at Broken Hill. Stevens (1999) observed that fold hinges (low strain zones) are preserved while limbs are the locus of high strain and intense, narrow shears, possibly associated with pegmatite generation.

What this recent mapping has shown is that the structural environment of the Broken Hill mining field, and the mineralised system, is not unique, and may prove to be a common mesoscopic and outcrop-scale structural style in the district. It shows that similar structures occur in monotonous, unmineralised sequences, such as the Sundown Group, as there are in the ore environment.

Some of the structural complexity attributed the Broken Hill mining field area may in fact be an artefact of the exponentially larger data density, compared with the surrounding region.

## 5.9. CONCLUSIONS.

The Broken Hill mineralised system and Lode Sequence predate all of the deformation that has affected the Broken Hill district.

The clastic metasediments of the Lode Sequence exhibit the penetrative S1 schistosity recognised by previous worker (Laing et al., 1978) and the entire package is intruded by large volumes of lode pegmatite, which may possess an S1 banding. Pegmatite dykes traverse the Lode Sequence stratigraphy, intrude the ore lenses and are common at the contacts of pelitic, quartzofeldspathic and psammitic units. D1 was not a significant event in the orebodies and was probably not associated with tectonism, at least in the BH region. Pegmatite was intruded into the MinSeq after the stratigraphy of the Lode Sequence was established and the architecture of the mineralised system was formed.

The mineralised system is not 'scrambled' by deformation and metamorphism but is largely intact and in place. The elongated geometry, and stratification of the mineralised system and its host Lode Sequence, preserves syn-depositional textures, internal stratification and layered gangue mineral distributions that predate pegmatite intrusion and F2 folding. The orebodies are conformable with the surrounding units of the Mine Sequence, even in the most intensely deformed areas and despite sulphide mobilisation in places. The observation of an original internal stratigraphy within the orebodies, which is conformable with a well-defined Lode Sequence stratigraphy in the mineralised system, shows that the orebodies are still largely in their site of deposition and form an integral part of the Mine Sequence. The stratigraphic relationships between the orebodies, their internal marker units, banding and interlayered metasediments, and the Garnet Quartzite and B Lode Horizons, were all established prior to deformation and metamorphism. Likewise were the relationships between 2L and 3L, and the 'underwall' zone of the Footwall Succession, also in place prior to deformation. The stratigraphy of the mineralised system, and its host sequence, is mostly intact and has been well documented in mining company records.

Mineralisation and the GQH traverse southwest plunging F2 fold hinges and five orebodies actually retain a trend that is 20° clockwise of the F2 hinges, even where overprinted by folding (2L, 3L, 1LU, 1LL, ALL). No significant preferential enrichment of sulphides in fold hinges has been observed. The orebodies are still

largely in their site of deposition and have not been moved on a mass scale by deformation, nor were they formed as a result of syn-tectonic epigenetic processes.

The orebodies and most lode rocks were in place, as a series of strongly elongated, lenticular bodies of sulphide-silicate-calcite mineralisation and manganiferous rocks prior to deformation and metamorphism. F2 folds traverse to the Lode Sequence stratigraphy and the orebodies, precluding any large or medium scale tectonic mobilisation of syngenetic mineralisation into structural sites during D2. They have not been moved on a mass scale by deformation. The elongate form of the system has been subsequently suppressed by fold convolution and accentuated by shear related attenuation of folds at subsequent stages in the structural history of the mining field.

All shearing post-dates D2 and has been a significant factor in the subsequent geometric modification of the orebodies. The effects of D3A shears have not been profound however, and they are confined to relatively narrow and discrete planes. Early D3A shearing has had the most significant effects in the orebodies and has formed a series of anastomosing shear arrays throughout the mining field, which have dislocated and attenuated F2 folds, often by as much as 750 metres (e.g. Figure 5.1, in separate map folder). All significant D3 shearing is sinistral, north-block up.

The Delamerian Orogeny had significant effects within the deposit and refolding of the Willyama Supergroup took place. Olarian structures within the orebodies are overprinted by D4 faults, dykes, folds and quartz-siderite galena veins.

There are significant variations in the intensity and style of structures associated with a particular deformation in different regions of the mining field and lithology can influence the types of features that are formed during any particular structural event. Observers must be aware of the structural, textural and stratigraphic variations that occur throughout the deposit, and consider them when drawing conclusions about aspects of the geology of the whole deposit when their observations are only made in one region.

The rocks of the Broken Hill mineralised system have responded to each of the deformations that have affected the mining field area. Structural fabrics have been formed in the ores and in their wall rocks during each of these events. Despite the effects of the successive deformations, there are still many well-defined, pre-

deformation and pre-metamorphic features preserved in the rocks of the Mine Sequence; in the Lode Sequence and within the orebodies. In fact, it is the pre-deformational features of the orebodies that have dominated its mineralogy and geometry to the present day, despite re-texturing, annealing, and a subsequent long retrograde metamorphic history. Deformation may have altered the geometry of the orebodies and their wall rocks, but it has not fundamentally changed the relationship between the orebodies; their Lode Sequence host; the Mine Sequence stratigraphy, or their place in the wider Willyama Supergroup. Pre-deformation features provide enough clear evidence to show that the elongation of the mineralised system was established prior to the peak of regional metamorphism. The Broken Hill mineralised system cannot therefore be the product of tectonic processes.

There are no structural indicators that can be used during exploration to suggest that a Broken Hill Type mineralised system was nearby. The Broken Hill mineralised system is a part of the sedimentary succession in which it lies and has been deformed and metamorphosed along with the other rocks with which it is interlayered. The structural environment of the orebodies is not unique within the Willyama Supergroup.

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## CHAPTER 6: LATER GEOLOGICAL HISTORY

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### 6.1. INTRODUCTION.

The Broken Hill orebodies were discovered because they outcropped as a visually distinctive ridge within a terrain of otherwise unremarkable low rolling hills. The outcrop of the orebodies formed a "broken" hill, with a curious asymmetry, which was surmounted in places by a ragged black capping. The cap set it apart from its surroundings and gave the hill its name. Early pastoralists in the district noticed this unusual landmark and named the paddock within which it lay the "broken hill paddock" (Farwell, 1948).

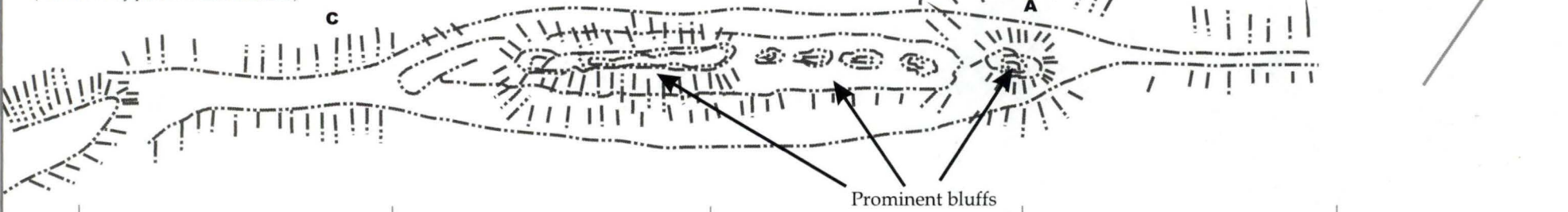
In this Chapter, the relationship between the conspicuous outcrop on the crest of the hill and the underlying, structurally modified geometry of the mineralisation is discussed. The discussion is focussed on the influence that the structure of the orebodies has had on their surface expression and on the geology of the extensive oxidised zone. The features recorded by previous workers in the outcrop; oxidised and supergene zones (eg. Marsh, 1893; Jaquet, 1894), or that are preserved in the remaining remnants of the hill are discussed in the light of the sub-surface geology.

The location, size, shape and mineralogy of the outcrop of the mineralised system is well recorded in photographs, published descriptions (both geological and laymans'), survey plans and geological mapping (e.g. Marsh, 1893; Jaquet, 1894; Andrews, 1922; Gustafson, 1939) (Figure 5.1, contained in separate map folder). Jaquet (1894), Swensson (1977) and van Moort and Swensson (1981) recorded the geology of many parts of the outcrop that have since been removed. Jaquet (1894), Swensson (1977), van Moort and Swensson (1981), Birch et al. (1988), Plimer (1984, 1988) and Birch and van der Heyden (1997) all described identifiable mineralogical zones within the oxidised portion of the lode. Some original outcrop remains (e.g. Figure 5.16). In combination with underground geological mapping, this information allows the relationship between the surface expression and the sub-surface geology of Broken Hill orebodies to be determined (Figure 6.1).



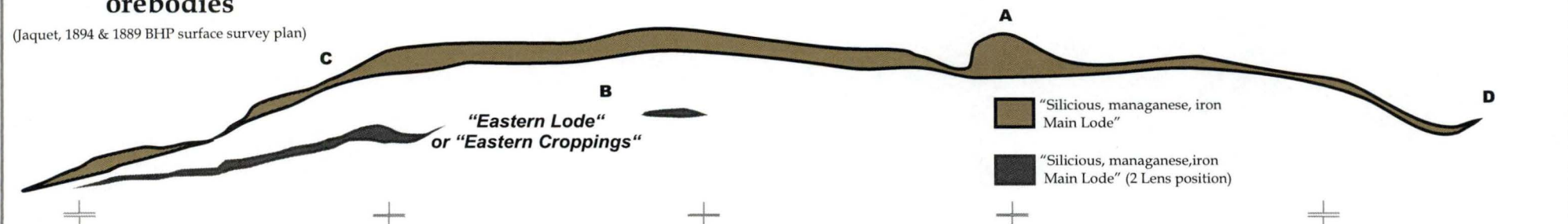
### 6.1a Outcrop topography of the "broken hill"

(From a survey plan of Broken Hill, 1887)



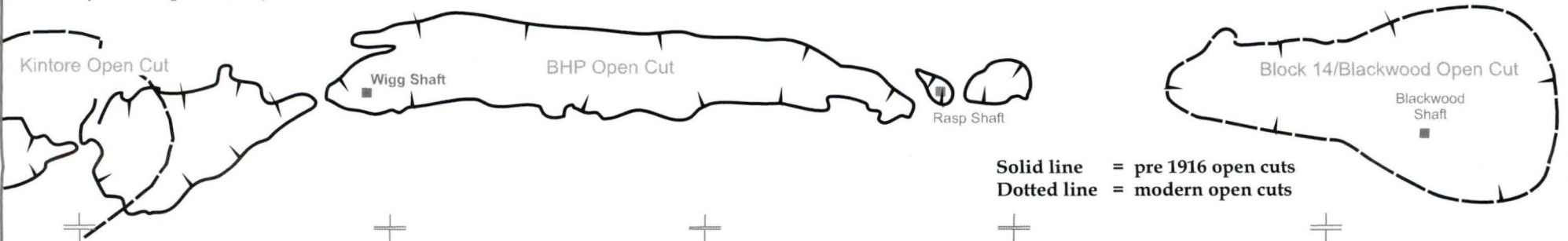
### 6.1b. Plan of the outcrop of the Broken Hill orebodies

(Jaquet, 1894 & 1889 BHP surface survey plan)

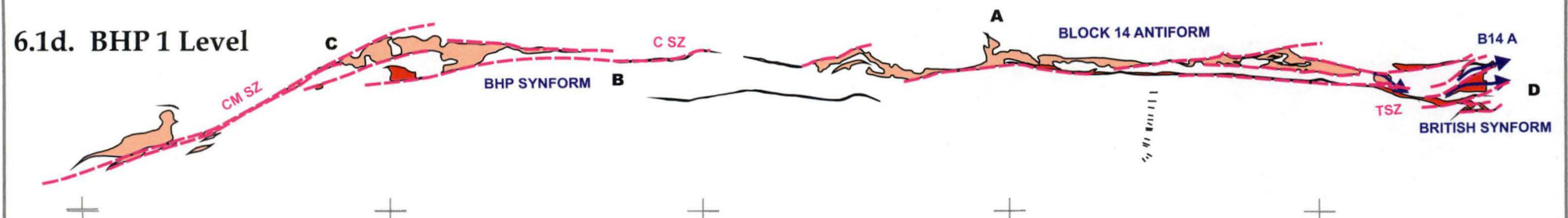


### 6.1c. Open cut positions

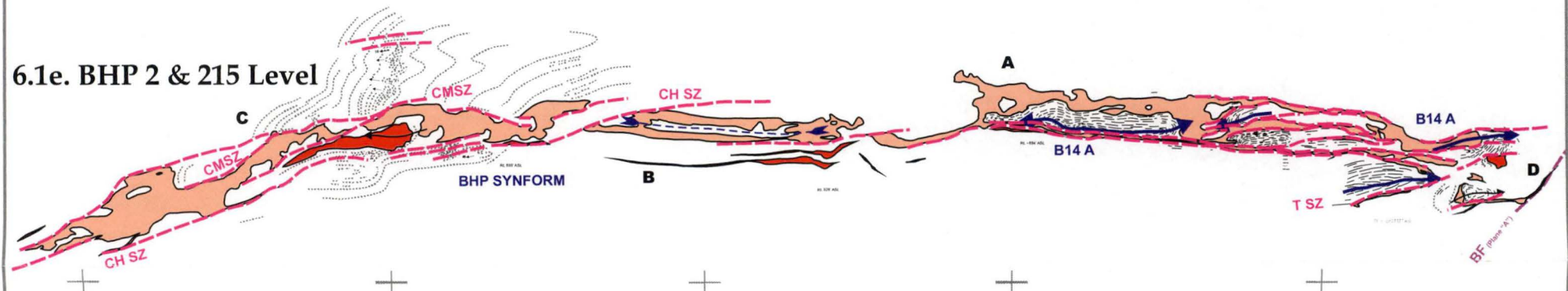
(From Gustafson 1939 & van der Haydon and Edgcombe, 1990)



### 6.1d. BHP 1 Level



### 6.1e. BHP 2 & 215 Level



### 6.1f. BHP 3 Level

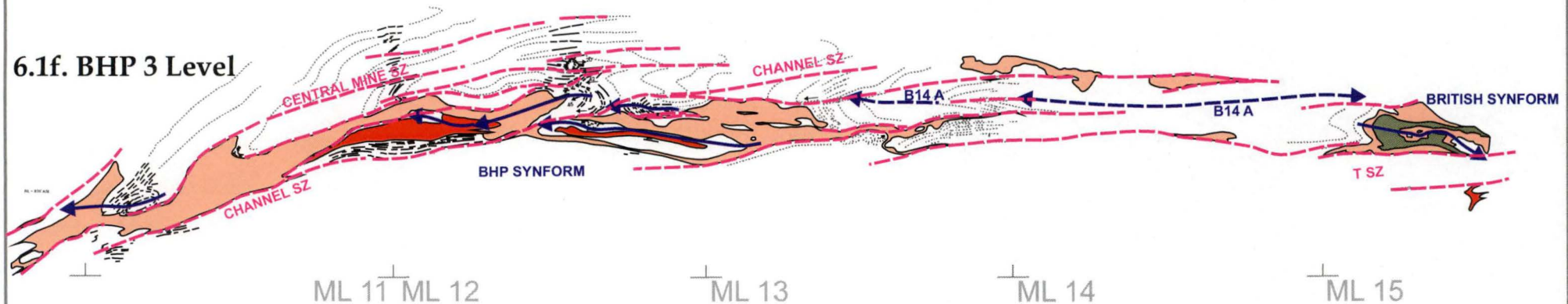
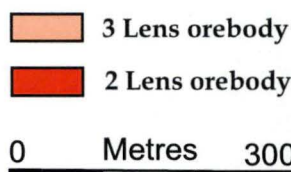


Figure 6.1 a to c. Series of plan views of the surface of the central region of the mining field. Note the relationship between the topography of the "broken hill" (6.1a) and the mapped surface expression of the lode (6.1b), and the positions of early and later open cuts (6.1c). The original ML boundaries are shown. 6.1a. Topography of the Broken Hill (from early survey plan). 6.1b. Surface outcrop of the orebodies mapped by Jaquet (1894), with additions from BHP survey plans. The "Eastern Croppings" or "Eastern Lode" is interpreted to be 2 Lens. 6.1c. Open cut locations.

6.1d to f. Consecutive geological plans of the upper levels of the BHP, Block 14, Central and Block 10 Mines (based on Gustafson, 1939). Structures and geometric features affecting 3L and 2L are also seen in the surface outcrop (Figure 6.1b) and control the original hill topography (Figure 6.1a). The geology of 2L and 3L in the upper mine levels can be directly correlated with the outcrop geology of the orebodies. Distinct geometrical features of the lode outcrop and hill topography that can be correlated with sub-surface geological features of the orebodies are labelled using capitalised letters. A: The hinge of the Block 14 Antiform, the only fold structure that can be recognised in the surface outcrop. B: The attenuated region dominated by the BHP Synform and the BHP Antiform within the BHP mine. The geology of the orebody sub-surface controls the outcrop geology of the lode. C: The change in strike from northeast southwest to south that begins at the southwestern end of the BHP mine. The southerly trend predominates throughout the southwestern part of the deposit. D: The position in which the Thompson shear terminates the northeastern strike of the mineralised system and offsets the orebodies to the north.





		<b>The Structure of the Broken Hill Lead Zinc Silver Deposit</b>		
<b>Relationships between surface features &amp; sub-surface geology, Central Region, Broken Hill Mining Field.</b>				
<small>Data Sources (where known)</small> Gustafson (1939), various sources (see individual captions)		<small>Author</small> A (Tony). E. Webster		

Figure 6.1

## 6.2. ORIGINAL OUTCROP PATTERN OF THE BROKEN HILL DEPOSIT.

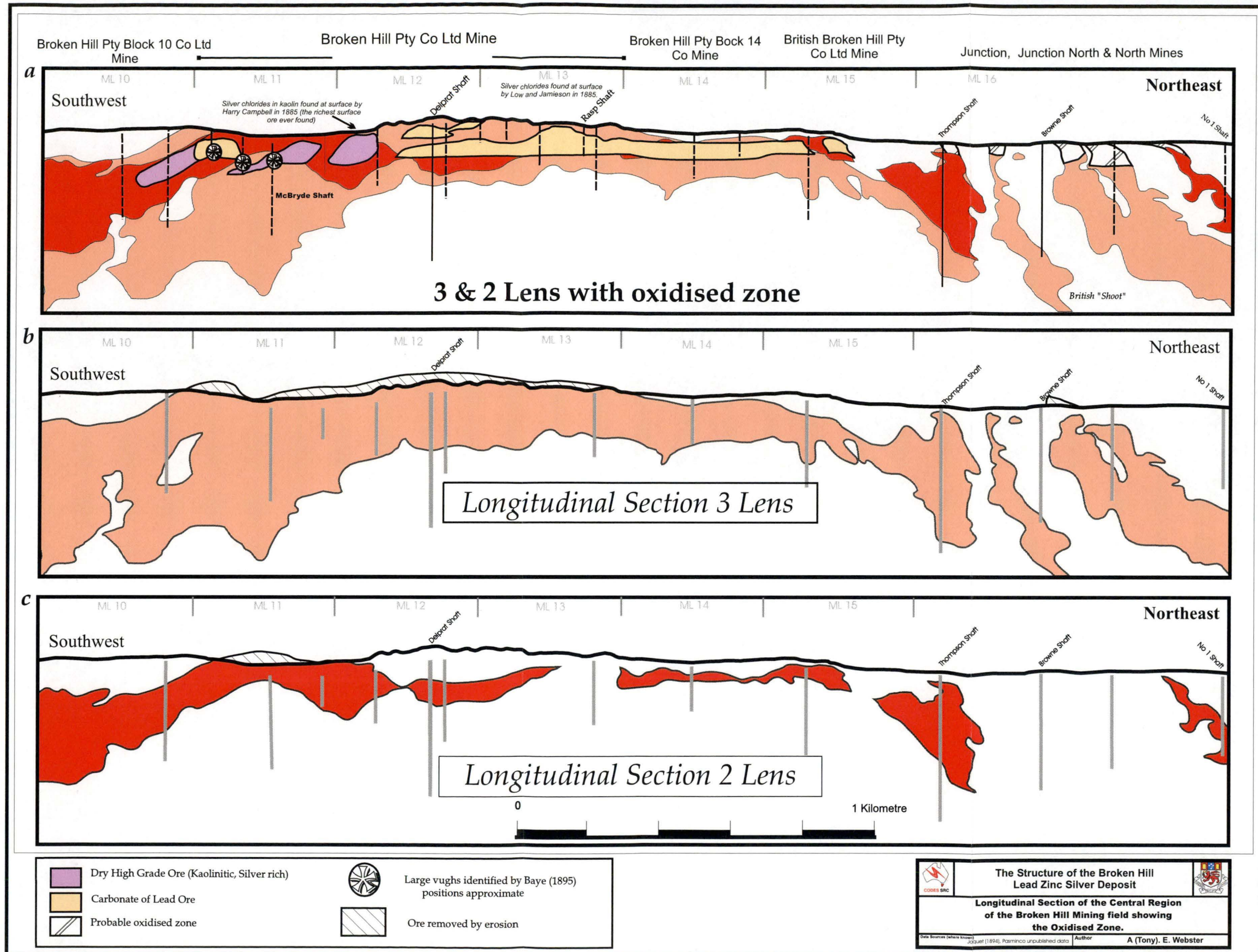
In 1883 the outcrop of the Broken Hill lode was a long narrow, northeast trending, strongly asymmetric ridge that sloped gently to the northwest, possessed a strongly bluffed summit and a steeper southeastern side (e.g. see Figures 5.17 and 5.18). It was composed of "ferruginous quartzite, quartz 'greisen', feldspar, porous brown iron ore or gossan and oxide of manganese, with patches and veins of crystallised carbonate of lead" (Wilkinson, 1884). There were sharp undulations at the crest on ML 12, 13 and 14, formed by a manganiferous and ironstone cap which stood boldly out from the surrounding metasediments, to a height of 15 or 18 metres (Blainey, 1968) (Figure 6.1a & b; Figure 6.2). Large blocks of "iron" and quartz had fallen from the capping and rolled down to the base of the hill on the southeastern side (Warren, 1903). The outcrop was highest near Patterson Shaft in ML 12 and there was a depression in the profile in ML 11 (Andrews, 1922) (Figures 6.1a & b and 6.2). Of all the lodes discovered in Australia in the 19th Century, Broken Hill probably had the most conspicuous outcrop (Blainey, 1968).

Manganiferous oxide was traceable for about 2.4 km, from opposite Kelly's Shaft in ML 10 to the British Mine No 2 Shaft in ML 15 (Figure 6.1b, and also Figures 4.1 & 5.1, in separate map folder). It varied from 6 to 30 metres thick, though the exact width was difficult to determine because of the accumulation of eroded debris on either side (Jaquet, 1894).

The most prominent manganiferous and ironstone outcrops were the first part of the hill to be pegged and the linear trend of the outcrop and ridge dictated the orientation and placement of the original mining leases (Figure 6.1). Even in ML 9, 8, 7 and 10 where there was no significant coronadite (lead-manganese oxide) outcrop, leases were still pegged.

From ML 15 to the North Mine No 1 Shaft (northeast end of No 1 Open Cut), the surface expression of the deposit is weakly weathered garnetiferous lode rocks with a coronadite patina and minor mineralised rocks. So the early prospectors recognised the strike of the manganiferous rocks and pegged their leases whether mineralised rock was showing or not.





**Figure 6.2.** Longitudinal projection of the central part of the Broken Hill mining field, looking northwest. The oxidised zone described by Jaquet (1894) is superimposed on 2L and 3L (modified after Gustafson, 1939). The original topography of the hill is shown in profile. The most prominent outcrop occurred in ML 11 to 14 and the first mineshaft was sunk on ML 13. Note the approximately horizontal "Carbonate of Lead" ore zone in ML 12 to 15 and the three southerly plunging shoots of "Dry High Grade" ore in ML 10 and 11. The latter ore shoots were the main wealth producing ore zones of the Central and Block 10 mines (containing extreme silver grades) and show a close spatial association with 2L. The geometry of the kaolin zones suggests that the F2 fold geometry influenced the re-deposition of silver and lead carbonates in the oxidised zone. There is also a close association between 2L and the large vughs recorded by Baye (1895).



The distinctive manganese and ironstone outcrop on ML12, 13 and 14 was only a minor part of the surface expression of the Broken Hill orebodies. The deposit was also represented at surface by lode rocks and other elements of the Lode Sequence stratigraphy (Johnson and Klingner, 1976). The Lode Sequence and distal Lode Horizon formed a prominent, discontinuous, narrow ridge rising up to 50 metres above the enclosing metasediments. This ridge can be traced for 25 kilometres, from the southern leases of the Pasminco Mine to Piesse's Nob (Johnson and Klingner, 1976; Larsen and Webster, 1996). The "broken hill" merged with this linear ridge to the northeast and southwest (Figure 6.2a).

Jaquet (1894) recognised that there was a structural control on the surface expression of the lode. He suggested that the extent of the lode outcrop diminished to the southwest because the "saddle" (or the main ore-bearing antiform) plunged southwest, away from the surface at the southwest end of the BHP Mine. As the orebodies became deeper, the prominence of the hill diminished. As Jaquet (1894) recognised, and as will be discussed in detail later, the geometry of the manganiferous outcrop (Figure 6.1) directly reflected the subsurface structure of the underlying orebodies. Strike changes, bulges and thinning in the manganiferous outcrop can be directly related to structures and strike variations in the underlying mineralised rocks (Figures 6.1a to f). The linear shape of the 'broken hill' reflected the geometry of the manganiferous outcrop and the prominent ragged cap lay directly above the shallowest part of the deposit (Figure 6.1 and Figure 6.2).

By the time of discovery, erosion had exposed the fringes of kaolinitic metasediments and mineralised kaolinitic zones at the topographic surface, mostly below the coronadite cap. Material could be dislodged from the outcrop by rainstorms as was witnessed by William Jamieson in 1884 (Bridges, 1920). Although there were large blocks of coronadite material lying in the scree slopes, they related to the highest point of the orebodies (the arch) that would have been the first part of the deposit to be affected by surface processes such as weathering and erosion. Jaquet (1894) was still able to deduce the approximate size and shape of the lode outcrop at surface even though there was scree material at its base.

The black manganiferous outcrop of the Broken Hill deposit is often called a gossan (e.g. Plimer, 1984; Birch and van der Heyden, 1997). Yet contemporary descriptions (e.g. Jaquet, 1894), more recent work (e.g. Swensson, 1977) and the remaining outcrop

show that most of the original outcrop was derived from the weathering of siliceous wall rocks to the orebodies, particularly the garnetiferous rocks. There was only a small component of the outcrop that was directly derived from sulphides and which can therefore be called a true gossan.

### **6.2.1. Remaining outcrop of the Broken Hill Deposit.**

Most of the original outcrop of the Broken Hill orebodies has been removed or is buried under mullock dumps produced by recent open cut mining. However, lode rocks and minor mineralised rocks associated with 3L and 2L outcrop to the northeast of ML 15, between Thompson Shaft and the Number One open cut of the North Mine. Examination of the surface mapping of Marsh (1893), Jaquet (1894) and Gustafson (1939) shows that this northern slope of the original hill is well preserved.

The lode rock outcrops consist of distinct folded bodies with complex geometric forms. They are mainly composed of banded 'garnet sandstone' or a garnet quartzite-like rock. This is a slightly weathered, friable, fine-grained garnet rock and is strongly banded with 0.5-2 centimetre zones of black manganiferous material (after sulphide?). The garnet quartzite is fine-grained quartz-garnet rock and is very hard. Manganiferous material is weakly developed on the outcrops and most are only coated in a coronadite patina (Swensson, 1977).

The most prominent outcrop lies at the Browne Shaft brace and forms a small razorback surmounted by strongly folded gossan and weathered manganiferous garnet sandstone. A cutting has exposed a section through the outcrop, which is shown in Figure 5.16). The next outcrop to the northeast seems to be largely antiformal, with a southwest plunge; as is shown by preserved banding. A linear series of smaller lode rock exposures continue to the northeast of Browne Shaft and consist of boudins that show that the orebody position is much attenuated in this area (as the underground mapping shows at depth, e.g. maps NTH1 to NTH4 in Appendix 1). Further to the northeast, towards Marsh Shaft, the outcrops are mostly covered in manganiferous rubble. All lode rock outcrops are enclosed within weathered, tightly folded and often sheared sericitic psammites and pelites.

The geometry of the outcrops is very similar to that of the steeply northeast plunging 3L and 2L seen in the underground levels immediately below the area. The outcrops

lie directly above the projected positions of these orebodies. Many workers have noted the association of garnetiferous rocks with the 'hanging wall' (Jaquet, 1894) and immediate updip positions of the orebodies (particularly 3L) in the northeastern section of the deposit (e.g. Dave Larsen pers comm. 1992; Schuler et al 1993; Lees, 1994; Lips, 1994). Thus the abundance of such rocks immediately to the northeast of ML 15 suggests that the orebodies and lode rocks lie at a shallow depth below surface. It is therefore certain that the lode rocks outcropping in the Thompson-Browne Shaft area represent the surface expressions of 3L and 2L.

Clusters of boxwork textured goethite (sulphide-derived gossan) up to one metre wide occur in patches, mainly on the northeastern slope of the main outcrop at Browne Shaft, however there is little other true gossan outcropping in this area (see below). The rarity of evidence for extensive sulphide mineralisation within these outcrops is important to the discussion of the near-surface structural interpretation.

Garnetiferous rocks are less common in the southwest in the Thompson Shaft area (Gustafson, 1939) and there is no record of significant occurrences until the boundary of ML 13 and 14 is reached. The possible reasons for this observation are discussed further below. Lode rocks also outcrop in the Pasminco mine at the southwest end of the field. They are discussed more fully below.

### 6.3. OXIDISED ZONE.

The oxidised zone of the Broken Hill deposit produced a rich variety of minerals. For details of the mineral species present see Lawrence (1968b), Plimer (1984), Worner and Segnit (1988); Birch and van der Heyden (1997). What is important to note is that mineral species were not randomly distributed in the oxidised parts of the deposit but occurred in distinct and structured mineralogical zones. Although workers differ on the zones they define, all have identified mappable, mineralogically distinct regions in the oxidised zone (e.g. Jamieson and Howell, 1893; Jaquet, 1894; Birch and van der Heyden, 1997). The locations of the mineralogical zones relate to deeper geological features of the orebody as well as to the original geometry, mineralogy and composition of the oxidised ores and adjacent rocks.

Jamieson and Howell (1893) were the first to identify and map the mineralogical zones within the oxidised portion of the orebodies. The different mineral complements of



the oxidised and partially oxidised ores (Figure 6.3) required different treatment and smelting processes and so were defined on that basis. Jaquet (1894), using BHP mining data, defined a series of mineralogical zones in the oxidised part of the deposit (Figure 6.3 and 6.2). Plimer (1984) also identified zones within the secondary alteration of the orebodies (Table 1; for minor components see Plimer's Table 4). Birch and van der Heyden (1997) identified mineralogical zones in the Block 14 and Kintore open cut (Figure 6.3).

The oxidised ore types are all closely associated with the central arch or plunge culmination in the centre of the field (Birch and van der Heyden, 1997) (Figure 6.2). It is mostly in this region of the mining field that mineralised rocks were close enough to the surface to be affected by surface oxidation and ground waters. Therefore, this primary structural feature of the deposit has played an integral part in the location of the rich and mineralogically diverse oxidised zone.

Within the oxidised zone there were many "irregular masses of zinciferous galena" encountered, the centres of which retained a primary zone mineralogy (Marsh, 1893). Such masses were interpreted to be zones of incomplete alteration of the primary sulphides. Therefore, oxidation of the primary sulphides was incomplete within the oxidised zone at the time of discovery.

Jaquet (1894) defined a zone of depleted material extending up to 70 to 100 metres below surface in his longitudinal section (Figure 6.2). Plimer (1984) suggested that the original base metal depleted manganiferous oxidised zone extended to an average depth of 75 metres, below which a rich but highly variable zone of oxidised minerals occurred. Van der Heyden and Edgecombe (1990) recognised that the depleted rocks extended to 100 metres depth, especially in the hanging wall and footwall of 3L. As will be discussed in a later section, in most parts of the outcrop area, the near surface zone of low base metal values is interpreted as a primary feature. It was not the result of near surface leaching of metals during surface oxidation.

### 6.3.1. Supergene Zone.

A supergene zone was present at Broken Hill at the time of discovery but it is considered to have been very small and poorly developed for a deposit of this size (e.g. Swensson, 1977; Plimer, 1984).

In ML 10, a zone of supergene silver enrichment was developed between the mineralised kaolin zones and the underlying sulphides. It was an irregular zone of black powdery leaching products and secondary sulphides described as “sedimentary sulphides”. It varied from a “few inches” to 75 centimetres thick. The richest parts of the zone were in contact with high-grade sulphide ore and it disappeared altogether where the sulphides diminished. The supergene zone was exceedingly rich in silver and where it was thickest, it contained silver and lead sulphides and large blocks of native copper. Semi-oxidised, commonly porous sulphides formed an upper crust to the supergene ores. The pores were often in-filled with the same black powdery material that was present in the “sedimentary sulphide” material (Warren 1903).

Jaquet (1894) recognised a zone of “secondary sulphide ore”, varying in thickness from 7.5 centimetres to approximately 1 metre. It consisted of sooty black material and was referred to as “sooty sulphide ore” by the miners. He observed that the material coated ordinary sulphides in places where “dry ore” was in contact with sulphide ore. It contained up to 250 ounces of silver per ton and up to 12% copper. In their discussion of Marsh (1893), Greenway (in Marsh, 1893) and Warren (in Marsh, 1893) both observed that the “black band” was warmer than the ores above (oxidised) and below (sulphide), to the extent that it could not be touched. These observations suggest that it was a highly reactive zone.

Swensson (1977) suggested that a large supergene zone had originally existed but that it had been remobilised and reduced by a later drop in the water table. A possible explanation for the small supergene zone developed at Broken Hill will also be discussed in a later section.

#### **6.4. GEOMETRY AND STRUCTURE OF THE MINERALISED ZONES IN MINING LEASES 10 TO 15.**

In this section the geology of the orebodies that was exposed on the 1, 2 and 3 levels of the former BHP, South, Central, Block 14 and British Mines will be discussed in reference to the surface outcrop and oxidised zone of the deposit.

#### 6.4.1. The BHP Mine (ML 11, 12 and 13).

The BHP Mine occupied the region of the plunge culmination; the place where ore and mineralised lode rocks came closest to surface and where the manganiferous ironstone outcrops occurred. The largest and most continuous of these lay in ML 12 (Figure 6.1a & 6.1b). As the BHP area occupied most of the deposit's significant outcrop area, it will be discussed in detail. The sulphide ore mined from underground and in the open cuts on the BHP mine was dominated by 3L rhodonite, rhodonite-''garnet sandstone'' and siliceous sulphide rocks (Jaquet, 1894; Andrews, 1922; Gustafson, 1939; van der Heyden and Edgecombe, 1990) (Figure 6.1c).

2 Lens was a minor ore source on ML 11, 12 and 13. It is thinned, attenuated and structurally dismembered throughout these leases (Figures 6.1d to f). It reached surface in ML 11 (Figure 6.1b & 6.2c) but otherwise lay at depth and only formed a significant component of the mineralised rocks of the oxidised zone in ML 11 and 12.

##### 6.4.1.1. *Structure of ML 11, 12 and 13.*

The geometry of the orebodies throughout most of ML's 11 to 13 is dominated by the complex interplay of the F2 BHP Synform and the D3A shears within its limbs; the Channel and Central Mine Shears (see Chapter 5). The geometry of the orebodies is also influenced by the zone of F4 folds that traverses the mining field in this region (mainly focussed to the immediate northeast)

The BHP Synform is shallow southwesterly plunging in ML 10 and the southeastern part of ML 11. The plunge reverses midway through ML 11 before returning to a shallow southwestern plunge again near the boundary of ML 12. From ML 12 to the northeastern end of ML 13, the fold is shallow southwest to horizontal in plunge. It was the zone of undulating, near horizontal plunge in ML 12 that formed the central arch of the deposit and which brought the mineralised rocks closest to the palaeosurface, within reach of the weathering processes.

The common limbs of the BHP Synform, Central Mine (CMA) and Block 14 Antiforms (B14A) are strongly sheared (D3A) and the fold hinges are attenuated throughout ML 11 to 13. A narrow 'sheet' of sheared sulphides and lode rocks projects upwards to surface from the common limb area of the BHPS and the B14A. It is mainly this material, with a small component of hinge zone ore, that outcropped in ML 12 to form

the prominent coronadite cap along the 'spine' of the 'broken hill' (Figure 6.1). The sheared mineralisation in the common limb of the BHPS and the CMA just reached the surface near the original crest of the hill between Darling Shaft and the northern boundary of ML 13 (e.g. Jaquet, 1894; Gustafson, 1939). In general however, the main body of mineralisation remained below surface but within reach of the surface oxidation. The large and mineralogically diverse oxidised zone was most extensively developed within the thick, pipe-like masses of 3L and 2L ore located within the hinges of the BHPS and the CMA in ML's 11 and 12.

The 2L and 3L orebodies are mainly hosted within the hinge of the BHP Synform throughout ML 11 to 13 but the fold diminishes in importance within the mineralisation to the northeast and the Block 14 Antiform becomes the main host of ore midway through ML 13. The hinge of the BHP Synform is lost due to attenuation and fold complications in the vicinity of Rasp's and Wilson's Shafts and it is this point where the orebody is at its thinnest (Figure 6.1b & 6.1d). The surface expression of the thinned mineralisation was the prominent outcrop on ML 13 and it is these outcrops that Rasp probably sampled in 1883 (Figure 6.1a & b). It is also in this material that the original syndicate sank their first shaft. The lack of ore at shallow depths in this shaft almost broke the group financially due to the very poor returns they initially obtained.

The manganiferous lode outcrop in the BHP Mine shows a strong spatial association with the structurally thinned 3L in the attenuated updip common limb position as defined on the BHP 1 Level (Figure 6.1b and 6.1d). The largest and most continuous outcrop on ML 12 corresponded to the thickest ore in this position on the 1 Level, while the four thin and discontinuous outcrops on ML 13 corresponded to the thinnest part of the mineralisation (Figure 6.1a & 6.1d). The geometry of the outcrop directly reflects the sub-surface geology of the mineralisation.

The dimensions of the original open cut in the Wilson's Shaft area and the mapping in this open cut by Swensson (1977) also show that mineralisation was very narrow in the near-surface region. It is suggested that the greatest development of manganiferous outcrop represents the surface expression of 3L and related lode rocks where they were thickest within the sheared common limb of the BHP Synform and the Block 14 Antiform and occupied the hinge of the latter. The prominent manganiferous outcrops on ML 12 and 13 reflect the position where mineralisation came closest to surface within the region of the F4 plunge reversal (Figure 6.2).

The BHP Synform, located on the southeastern side of the deposit, was best developed in the region near the boundary of ML 11 and 12. 2L mineralisation was restricted to a thin, dismembered segment preserved within the keel of the synform and formed a vertical to steeply dipping shoot within the fold keel (Figure 6.1d to f). The shoot outcropped as the “Eastern Lode” identified by Jaquet (1894) (Figure 6.1b). It probably formed the primary source of the silver in the silver-rich kaolinitic mineralisation found at surface at the boundary of ML 11 and 12 in 1885 and which was later mined from underground (Figure 6.2).

#### 6.4.1.2. *Oxidised ore type distribution.*

The richest ore type of the oxidised zone was the kaolin-dominated mineralisation that Jaquet (1894) named “dry high grade ore” (DHG). It contained silver grades of 900 to 9000 g/tonne Ag and 5% Pb and was best developed in three southerly plunging “shoots” at the boundary of ML 11 and 10. While it is difficult to determine the exact position of the DHG, it does show a spatial relationship with the dismembered BHP Synform and the 2L mineralisation contained within it (Figure 6.2a).

The southerly plunge of the dry high grade ore shoots is a curious feature of a supergene style of mineralisation which might be more readily expected to be horizontal and suggests that there was some geological control, other than the water table, on its development. Kaolin, the main constituent of DHG, is also an unlikely product of the break down of sulphides. So it is unlikely that the DHG ore shoots were formed in situ directly from the weathering of sulphide ore. A more likely explanation is that this ore type formed within leached and kaolinised metasediments lying within the keel of the BHP Synform. Swensson (1977) identified kaolinised metasediments throughout the oxidised zone at Broken Hill and showed that they were produced as the result of the leaching and weathering of clastic metasediments.

Silver-rich solutions originating from the weathering of the sulphide mineralisation may have been channelled down the synformal keel and deposited silver, as bromian chlorargyrite (Birch and van der Heyden, 1997), in the clay as it went (as was suggested by Jaquet, 1894). The BHP Synform is southerly plunging in this area as is the infolded mass of clastic metasediments and 2L mineralisation within its keel. So this early fold structure may have controlled the oxidation and leaching of the

metasediments and mineralisation, and focussing re-deposition of the silver within the kaolinised rocks.

#### 6.4.1.3. *Vughs.*

A concentration of open space vughs ranging from 4.5 metres x 1.8 metres x 1.8 metres to 2.7 metres x 4.5 metres x 12 metres, were developed in "the heart of the ironstone body" (Baye, 1895); probably the equivalent of Plimer's (1984) Oxidation Collapse Zone, in ML 11. Vughs of such large size were not common elsewhere in the BHP or other mines. While it is no longer possible to determine exactly where such vughs were developed, the available evidence (Baye, 1895) suggests that they were spatially associated with the 2L mineralisation within the BHP Synform and developed at the oxidised ore-fresh ore interface (Figure 6.2a).

Mining lease 11 is one of the few parts of the field where significant masses of 2L mineralisation reached the oxidised zone and it may have been more susceptible to dissolution and cavity formation than 3L ore. Leached 2L ore was found on the 2150 Level of the North Mine by Garretty and Blanchard (1942) who suggested that leaching had penetrated to such depths because of the solubility of the carbonate gangue. There was no leaching in the adjacent 3L mineralisation.

#### 6.4.1.4. *Mineralised rocks at surface.*

Silver-mineralised rock was rare in the manganiferous outcrop in the BHP Mine. William Jamieson only discovered outcropping kaolin-hosted silver chlorides assaying 800-1000 ounces of silver following a storm washout in 1885 (Solomon 1988; Blainey 1989). This was probably on ML 13. The richest ore found at surface was discovered by Harry Campbell in 1885, in a previously un-prospected part of the hill (Figure 6.2a). It consisted of kaolinitic silver-rich mineralisation below a thin manganiferous cap, (Bridges, 1920).

No mention of lead carbonates, lead chlorides or weathered sulphides (boxwork type textures) is found in early geological descriptions of the surface outcrop (e.g. Jaquet, 1894). However, gossanous goethitic boxworks after sulphides were found in outcrop by Swensson (1977), in the Browne Shaft area on ML 39. Silver chlorides and silver carbonates were only rarely seen at surface during early mining development (Blainey



1968) and the native silver slugs that had attracted the early prospectors to the Thackaringa area were unknown.

Jaquet (1894), Plimer (1984) and van der Heyden and Edgecombe (1990) all record a lead-silver-zinc depleted zone in the upper 60 metres of the deposit. Even in 1894, when the mining of the oxidised ore was waning, little mining had taken place in the top 30 to 60 metres of the lode (Jaquet, 1894, Figure 6.2a). It was only when open cutting of the outcrop began that significant mining of the upper 60 metres of the oxidised mineralisation took place implying that the silver and base metal values of this material must have been very low.

The geology of the upper levels of the BHP mine shows that most near-surface 3L mineralisation lies in the attenuated limbs of the BHP Synform. Two larger ore masses reached surface in ML 12 and near the ML 13 and ML 14 boundary. These two larger masses represent a small section of the hinge of the BHPS (the southwestern mass) and the common limb of the BHP Synform and the Block 14 Antiform (north-eastern mass) (Figure 6.1d). The ore only reached the surface in any significant way over a maximum strike length of approximately 720 metres in ML 12 and 13. Geological mapping and cross sectional interpretations by Jaquet (1894) and Gustafson (1939) show that the ore was mostly contained within the BHP Synform throughout the outcrop area and did not reach surface.

Northeast of ML13, the orebodies were hosted within the Block 14 Antiform. The hinge of this fold remained intact throughout the outcrop area and the poorly mineralised, sheared fold closure region (the "backbone" of the lode) was just being exposed at the crest by erosion when mining commenced. The coronadite outcrop and the underlying "Manganiferous iron ore" zone of Jaquet (1894) was poorly mineralised on ML 11 to 13 because they were not directly derived from sulphide mineralisation not because they were residual gossans left from the supergene leaching of ore. They were weathered equivalents of sulphide-bearing garnetiferous wall rocks and adjoining clastic metasediments that represented the "backbone" of 3L within the hinge of the Block 14 Antiform and BHP Synform, brought to near the palaeosurface by the arch of the plunge reversal. The rich secondary and oxidised ores intersected at depth, such as Jaquet's (1894) "Carbonate of Lead Ore" (Figure 6.2a) represent true sulphide-derived oxidised mineralisation.

The heavy black samples collected by Charles Rasp in 1883 were assayed but contained only minor silver and lead (Blainey 1968) and it is reasonable to assume that the material he collected was plumboan coronadite which van Moort and Swensson (1982) found could contain between 5 and 25% lead. If it is assumed that Rasp pegged his first lease and sited his first shaft in the vicinity of his assayed samples then it may be reasonable to assume that one of the prominent outcrops on ML 13 is the discovery outcrop of Broken Hill.

Rasp's Shaft lay directly over the most structurally thinned and poorly mineralised part of 3L in ML 13 (Figures 6.1c & 6.2a). Swensson's (1977) mapping of the oxidised zone exposed in the northeast face of Wilson's open cut, close to Rasp's Shaft, shows that the coronadite outcrop was developed on "lode quartzite" and "sillimanite gneiss". In hindsight, it is likely that the Broken Hill deposit was discovered by sampling material that was ultimately derived from metasediments and lode rocks, not massive sulphide mineralisation. The discovery outcrop also lay in the most structurally thinned part of 3L.

#### 6.4.1.5. *Open Cut Mining.*

Two phases of open cut mining occurred at Broken Hill. The first took place between 1891 and 1905, reaching 1.2 kilometres in length and a depth of 90 metres (Kearns, 1996b). The second took place between 1973 and 1991. Most of the original outcrop from ML 8 to ML 14 was removed during the first phase (Figure 6.1b & c). However, this material was not mined to extract its content of silver and lead, as this was generally very low. Several of the mines had suffered major collapses due to poor ground support techniques. The ground slippages ("creeps") caused severe damage to the processing and smelting infrastructure clustered closely around the hill. The lode outcrop was therefore initially mined by open cut methods to remove the overburden from the underground workings, thereby diminishing the pressure on the poorly supported stopes of the upper levels of the mines (Andrews, 1922).

Open cut mining of the outcrop was also undertaken as a source of siliceous flux for the smelters that were then operating on the field. The material did contain some silver and lead, with 32,000 tons of material grading 18% lead and 7 to 40 ounces silver being mined at one time (Blainey, 1968). Jaquet (1894) describes the open cut mining as producing ore in 1892. Later, he discusses the economic benefit to the BHP smelters

by being self sufficient in silver-bearing ironstone flux, which they were mining from the “back of the lode”. The silver content of the flux offset some of the smelting costs. The open cut mining persisted after the smelters were shut down in Broken Hill and did produce some ore grade material.

#### **6.4.2. The Block 14 Mine (ML 14).**

3 Lens is the only significant orebody to occur in ML 14, where it is expressed as high-grade rhodonite-bustamite mineralisation containing large masses of sulphide-poor rhodonite-bustamite. The size of the orebody increases through ML 14 and into ML15, to reach its greatest size near Blackwood’s Shaft on ML 15. The development of rhodonite-bustamite is also greatest in this region. 2 Lens does not outcrop in this area and is thin and attenuated throughout (Figure 6.1b & 6.1d).

##### **6.4.2.1. Structure of ML 14**

The geometry of 3L is simple in ML 14, lacking the convolutions and intense shearing of the BHP Synform to the southwest. The orebody geometry is mainly controlled by a single broad, tight antiform, which comes into prominence to the northeast of Rasp’s Shaft on ML 13, and which persists into ML 15 (Figures 5.17 and 5.18). This is the Block 14 Antiform (B14A).

A complementary tight to isoclinal synform lies to the south of and parallel to the B14A and is named the British Synform. The synform is poorly developed and is strongly modified by shearing along the southeastern margin of the orebody. Shearing is particularly focussed in the common limb of the two folds (Figure 5.18, Figure 6.1e & f).

The axes of the B14A and the British Synform are generally horizontal but undulate in plunge from shallow southwest to shallow northeast. From near the boundary with ML 15, the plunge become progressively steeper to the northeast, to the point where the orebody is truncated at depth by the Thompson Shear (see Chapter 5).

3 Lens is mostly focussed in the northwestern limb of the B14A in the southwest of ML 14 but gradually migrates across the fold hinge to the northeast, crossing the hinge in the region of the ML 14- ML 15 boundary. 3 Lens is thus “draped” across the hinge of

the antiform, while defining both the southern and northern limbs of the fold. In the vicinity of Blackwood's Shaft, the main mass of 3L enters the hinge of the British Synform, just south of the position where the Thompson Shear truncates it (Figures 5.12 & 5.18, see below). 2L mineralisation is only preserved on the 1 Level of the British Mine within the keel of the British Synform and is sheared out at depth by the Thompson Shear on the northeastern boundary of the mine.

Shearing is present within the common limb of the B14A and British Synform throughout ML 14 and 15, with an apparent west block up movement. Only thin, shear hosted mineralisation projects upwards from 3L in the B14A hinge zone to form a linear lode outcrop throughout ML 14 and 15 (Figure 6.1a, b & c and see also Figure 5.18). Consequently, the topography of the hill is subdued, coronadite development is minimal and outcrops of weathered and fresh garnetiferous lode rocks are well preserved in places (e.g. Gustafson, 1939). This is discussed further below.

#### 6.4.2.2. *Outcrop and Oxidised Zone on ML 14.*

The hinge of the B14A remains at depth throughout ML 14 and 15, however it intersected the topographic surface near the boundary with ML 13, where it was represented by a distinct bulge in the outcrop. This point directly overlay the hinge of the antiform in the upper levels of the Block 14 Mine (Figure 6.1b, d & e). This bulge in the outcrop also corresponded to a distinct, prominent coronadite outcrop at the ridge crest (Figure 6.1b). Except for the bulge, all other surface expression of the mineralisation on ML 14 can be related to attenuated ore, or lode rocks, lying updip of the modified antiformal hinge, or the sheared common limb of the B14A and the British Synform. The B14A is probably the only fold structure within mineralisation that outcropped on the original hill.

Surface oxidation affected the large volume of 3L mineralisation lying at depths of 20 to 60 metres below surface, in the sub-horizontal hinge of the B14A on ML 14 (Jaquet, 1894; Birch and van der Heyden, 1997) (Figure 6.2a). Thinner, attenuated mineralisation and lode rocks that extended above the hinge to surface were the focus of coronadite development and were shown by Jaquet (1894) as a depleted zone on his longitudinal section (Figure 6.2a). Workers such as Plimer (1984) and van der Heyden and Edgecombe (1990) recognised such near-surface, low grade manganiiferous oxidised zones and described the rocks as metal "depleted". However, the structure of

ML 14 shows that the low-grade zone was developed on a part of 3L that was structurally thinned and probably low grade prior to oxidation. The poorly mineralised rocks in this area were a primary feature of the deposit and not the result of large scale leaching of metals.

## **6.5. THE BRITISH AND JUNCTION MINES (ML 15, 16 AND 39).**

Northeast of the centre of ML 15 to ML 16 and 39 the lode outcrop becomes markedly less prominent as a topographic feature and changes strike, swinging 40° to the north (Figures 4.1 & 5.1). The surface and near-surface geology of this region is dominated by lode rocks and minor mineralisation associated with 3L. No 2 Lens is insignificant near the surface, though it increases in significance with depth to the northeast (Figure 6.2, see also maps BRIT1 to BRIT10 in Appendix 1). Outcropping lode material is dominated by variably leached and oxidised garnet quartzite and garnet sandstone with patches of gossanous, boxwork-textured goethite and is coated in a coronadite patina (Swensson, 1977).

### **6.5.1. Structure of ML 15, 16 and 39.**

As in ML 14, the British Synform and the B14A are a major controlling factor on the orebody geometry in ML 15, 16 and 39. However, the fold plunges progressively steepen to the northeast of ML 14, reaching 40° in the centre of ML 15 and 60° at the northeastern boundary of ML 16. This results in an abrupt decrease in the occurrence of lode rocks and mineralised rocks at surface (Figure 6.1b & Figure 5.1). In ML 15 only minor mineralised rocks occur at surface and only small patches of lode rocks are present. Such occurrences are virtually absent in much of the centre of ML16 (Figure 5.1).

Midway through ML 15, two shear/fault structures known as the Thompson Shear (Olarian age) and the British Fault (Delamerian age) develop and they have a significant effect on the geometry of 3L and its lode rocks, both at depth and near surface. The shearing is the major influence on the lode outcrop between ML 15 and the northeastern boundary of ML 16, producing a sharp northerly swing in the strike of the lodes which commences on ML 15 (Figure 5.1, Figure 6.1b).

The Thompson Shear, which is a broad tabular, slightly sinuous, steep easterly dipping structure comes into prominence on the southeastern side of the orebodies in ML 14 and persists well into the North Mine area. It intersects the folded geometry of the orebodies at a low angle (approximately 30°) and produces a 300 metre sinistral offset in 3L and 2L, where they lie within the hinges of the B14A and the British Synform. The northeast block is displaced approximately 350 metres vertically, in a reversed sense (Figure 6.2). A dislocated block of rhodonite-rich 3L ore, within the keel of the British Synform in this shear zone was mined as a separate orebody. It was variably referred to as the British Orebody (Boots, 1972) or the British Shoot (Henderson, 1953) (Figure 6.2).

Early company geological mapping of the upper levels of the British and Junction Mines shows that the mineralised rocks in the Thompson Shear are structurally thinned, with several larger pods of 3L sulphide (relict fold hinges?) preserved within them. Wider pods of 3L sulphide or lode rocks preserve evidence of pre-existing fold geometries in the form of remnant fold hinges defined by banding. Pods such as this outcrop adjacent to Thompson Shaft and on the Menindee Road and were mapped in detail by Andrews (1922) and Gustafson (1939). The prominent manganiferous outcrop hosted within siliceous sericite schist on the northern side of the Menindee Road is the surface expression of one such pod that has been further modified by later quartz-sericite-biotite shearing. At depth, below these outcrops, large bodies of mineralisation are hosted, or partly hosted within the Thompson Shear.

Subsequent development of the east-dipping (65° to 85°) British Fault produced 100 metres of apparent strike slip offset in the Thompson Shear. Yet, while the multiple planes of this fault may have produced significant reversed, northeast block up movement between the North Mine area and the Central Region (BHP-Block 14 area), the majority of the structural attenuation and offset in 3L and 2L was present before the fault developed.

#### **6.5.2. Menindee Road-Browne Shaft Area (ML 16).**

The part of ML 16 between Thompson Shaft and Browne Shaft contains outcropping thin, poorly developed and sinuous garnet quartzite, coronadite-rich rocks and garnet sandstone that reflect the sheared and structurally thinned orebodies at depth. All of these outcrops, including the sinuous, tabular and lenticular bodies of lode rocks and



segments of 3L are associated with larger, shear and fault-dislocated bodies that lie within the Thompson Shear.

The most significant outcrops of mineralisation and lode rocks in the Thompson Shear are possibly pre-shearing fold hinges (F2) that have retained some degree of their original geometry. The strong swing in the strike of the outcrop reflects the strike of the Thompson Shear and to a lesser extent, the British Fault Zone and its associated F4 folds.

### **6.5.3. The Browne Shaft and North Mine areas (ML 16, ML 17 and ML39).**

The Junction and North Mines lie northeast of the Thompson Shear (ML 16 and 39). Mineralisation is dominated by 3L though 2L is significant. The area possesses the first significant outcrops of manganiferous lode rocks northeast of the thinner shear hosted orebody fragments within the Thompson Shear.

Surface mapping compiled by Gustafson (1939) shows that distinct and recognisable outcrops of folded 3L, dominated by garnetiferous lode rocks, occurs immediately to the northeast of the Browne Shaft collar. Prominent manganiferous garnet sandstone and kaolinised psammitic metasediment reappear at the crest, adjacent to the Browne Shaft brace (Figure 5.16) and the topography of the hill becomes more prominent than it was on ML 14, 15 and 16. The strong development of 'garnet sandstone' in the lower southwestern corner of this outcrop is the footwall of 3L while the main crest is composed of the gossanous remains of the 3L orebody. A smaller lode outcrop immediately northeast of Marsh Shaft sill is interpreted to be 2L. Both these outcrops are extant.

The folded geometry of the outcropping mineralised rocks define distinct bodies of 3L and 2L that have exactly the same three dimensional geometry as is observed on the upper levels of the North Mine from the 1 Level to the 6 Level. Therefore, these outcrops are interpreted to represent the definite surface expression of the main orebodies at Broken Hill.

The Browne Shaft 3L and 2L outcrops are only weakly mineralised, with minor patches of boxwork gossan associated with white quartz and blue quartz veining. The majority of the outcrops consist of garnet quartzite, which has been variably silicified

or altered to garnet sandstone. Coronadite is variably developed as a patina. Garnetiferous rocks, including an alteration rock known as 'GO rock' by company geologists and garnet sandstone are well developed adjacent to 3L in the upper levels of the North Mine where Jaquet (1894) first recorded them. The spatial association of 'GO rock', garnet quartzite and garnet sandstone with the footwall of 3L is well known, having been recognised by many earlier workers (e.g. Henderson 1953).

The No 1 Open Cut of North Mine lies northeast of the 3L outcrop at Browne Shaft and the 2L outcrop at Marsh Shaft. Therefore, the ore that was mined in this open cut was attenuated streaks and fragments of the main orebodies that was distal to the main mineralised position. Adjacent to North Mine No. 1 Shaft, in the outcrop recorded by Swensson (1977), the manganiferous lode rocks likely represent the weathered surface expression of this distal mineralisation and its associated lode rocks.

#### **6.5.3.1.        *Structure of ML 16 and the southwestern North Mine.***

Isoclinal folds dominate the geometry of 2L and 3L northeast of the Thompson Shear. However, the fold geometries are suppressed and the orebodies have a strongly lenticular shape that has been described as a flat sheet by workers such as Hobbs (1966). Folds become more evident below the 12 Level.

The orebody geometry that is observed in outcrop and in the upper levels of the North Mine (Figure 5.16) is controlled by transposed isoclinal folds that represent the direct continuation of those in ML 15, southwest of the Thompson Shear. Similar fold geometry is evident in the shear-bounded fold structures that affect 3L and 2L at depth in the British Mine. 3 Lens and 2 Lens outcrop to the southwest of the main area of the North Mine and surface outcrop there is formed from structurally attenuated fragments of the orebodies, altered metasediments and garnetiferous lode rocks.

The apparent reversed dip slip movement of the Thompson Shear resulted in 3L and 2L being uplifted in the Browne Shaft-North Mine area, relative to the southwestern block and therefore brought closer to the surface than they were in the Block 14 and British Mine areas (Figure 6.2).

## 6.6. THE CENTRAL, SOUTH AND PASMINCO MINES.

Southwest of the ML10 and 11 the outcrop of the mineralised system is subdued and the only significant mineralised rocks at surface are thin, attenuated 'strips' of sulphide, hosted within a high-grade shear zone; the Main Shear which forms a subordinate plane of the BOA Shear System (Gustafson, 1939; this study). This structure is a high-grade shear zone with a sinistral, west block up sense of movement (Webster, 1993; 1994a). All sulphides and gossanous derivatives at surface in this area are weak, structurally thinned and shear hosted. Lode rocks are not prominent at surface. Consequently, the outcrop of mineralisation was poor and there is no prominent manganiferous outcrop developed. The Belt of Attenuation has a more southerly strike than the high-grade folds that control the deposit geometry to the northeast. In ML 11 and 10, the result of the Belt of Attenuation at surface is a distinct, 30-degree change in the strike of the outcrop to the south that persists throughout the outcropping lode rocks on the Pasminco Mine.

The far southwestern end of the of the "broken" hill; known as South Hill, represents the surface expression of the multiple orebodies lying at depth in the Pasminco Mine. A blue quartz-gahnite-garnet-rich horizon and a series of thin and lenticular garnet quartzite and garnet sandstone bands outcrop here and represent the distal positions of the orebodies at depth (Figure 4.1, 4.10c & 5.1). The relative abundance of such lode rocks in outcrop contributed to the prominence of southwestern end of the original ridge. However there is no visible evidence that there was any significant outcropping sulphide, so the multiple orebodies that occur at depth in the Pasminco Mine do not intersect the present topographic surface. 3L and 2L are the only orebodies that outcropped at Broken Hill.

## 6.7. DISCUSSION.

An understanding of the relationship between the subsurface geology and the surface expression of the Broken Hill deposit allows an estimate of the erosional loss of ore from the deposit to be made. This estimate will help to determine the absolute size of the type example and world's largest Broken Hill Type deposit, which in turn will constrain models of metal derivation from the crust.

The only part of the Broken Hill field where the orebodies outcropped was within ML 12 and 13, where the most jagged ridge outline was found. This mineralisation was almost solely 3L. Structural interpretations of the area based on the underground mapping show that near surface, 3L lay largely within the severely attenuated Central Mine and Block 14 Antiforms and in their associated synforms, the BHP Synform and the British Synform. However, the mineralised rocks that do occur at surface are located in the sheared updip hinge and common limb positions of these folds. As 3L is largely intact within the attenuated antiformal closures, it can have only lost minor volumes of ore during recent erosion.

The thinning of 3L must be a feature of the deformation of the orebody developed during Olarian folding and shearing (Webster, 1994a, 1996a, this study). Structurally thinned 3L outcropped for approximately 730 metres of strike length but the resilience of the ironstone-coronadite cap and garnetiferous lode rocks preserved the main mass of the orebody from erosion.

2 Lens is thin and discontinuous throughout the outcrop area, being mainly preserved in the keel of the BHP Synform. If 2L was present in the hinge of the Block 14 Antiform, then it too would probably have been strongly attenuated. Therefore, the tonnages of mineralised rock lost to erosion from 2L would have been minor.

#### **6.7.1. Mineralogy and Derivation of the Outcrop.**

At Broken Hill, it cannot be demonstrated that the surface expression of the orebodies contained a significant sulphide component prior to oxidation and weathering and was therefore not a gossan as previous workers have suggested (e.g. King and O'Driscoll, 1953; Plimer, 1984). All available evidence suggests that the surface expression consisted of the weathering products of siliceous rocks associated with the orebodies (e.g. Gustafson, 1939; Swensson, 1977; van Moort and Swensson, 1982). True gossan only becomes a significant proportion of the oxidised zone at depth (e.g. Jaquet, 1894; Plimer, 1984; van der Heyden and Edgecombe, 1990). It can consequently be deduced that only minor sulphide mineralisation was present in the rocks that formed the surface exposure of the Broken Hill deposit. Sulphides were present in the rocks but probably in similar proportions to that in the Browne Shaft outcrop on ML 16 (Figure 5.16). Most of the outcropping lode material was manganiferous and siliceous material derived from silicates.

### 6.7.2. Loss of Ore to Erosion.

A longitudinal section of the deposit was used by Plimer (1984) to estimate that 60 million tonnes of ore containing greater than 25 percent metal was lost from the deposit by weathering and erosion. However, this estimate is inaccurate for the following reasons.

1. Four separate stratiform orebodies are represented on this long section; 3 Lens, 2 Lens, B Lode and Southern A Lode. These do not form one single mass of ore as the long section suggests;
  2. Plimer (1984; his Figure 1) joined the hanging wall of BL in the southwest to the northeastern margin of 3L in the northeast and assumed continuity for the entire length of the field. However, the B Lode orebody nowhere reaches surface. Only one small section of 3L outcrops near the North Mine (at the Browne Shaft locality) and 2L is only represented at surface by gossanous, weakly mineralised rocks. Projecting the upper surfaces of the orebodies in this way also fails to take into account the vertical displacement of the northeastern section of the deposit by the Thompson Shear and British Fault in the British Mine, just to the northeast of ML 15. In reality, the upper surface of 3L in the southwest can only be projected to 3L in the northeast at a position just southwest Blackwood Shaft on ML 14, and not to the North Mine.
  3. Long sections such as Plimer's (1984) Figure 1 show an outline of all ore that has been mined and defined for mining. Therefore, such diagrams include both the main mass of the mineralisation and subsidiary ore; particularly that contained in shear zones (such as the Belt of Attenuation). 2 Lens shear zone ore is thin but continuous at the southwestern end of the field but when included in longitudinal projections it can cause the impression that a large mass of 2L reaches the surface over a 200 metre strike length in the southwest. However 2L shear ore was not mined to surface, and where it does outcrop, it is less than two metres wide. In addition, there is no record of any significant lode outcrop southwest of ML 10.
- 3 Lens and 2L lessen in width and down dip extent to the northeast of ML 12 to 15. This is not due to loss of ore by erosion. Overly simplistic longitudinal sections of the deposit contribute to the impression that both orebodies become reduced in vertical extent only in the outcrop area. However, the apparent reduction in down dip extent

of 3L and 2L at depth northeast and southwest of the outcropping orebodies is an effect caused by a combination of smaller ore lenses, intense Olarian folding (which convolutes the orebodies) and the greater attenuation in the centre of the field.

4. 3 Lens is the only orebody that is continuous for the entire length of the deposit. 2 Lens is dismembered, severely attenuated and only preserved in attenuated synformal keels in the centre of the field.

Plimer (1984) suggested that there should have been an extensive zone of secondary enrichment developed at Broken Hill if 60 million tonnes of ore have been weathered away. Yet such a zone has never been found (see above). He identified this as an enigma but suggested that the metal may have been transported away in solution. It is suggested here that the secondary zone was thinly developed, though rich, simply because weathering affected a relatively small percentage of the original orebodies.

The majority of recorded evidence shows that there has only been a small tonnage of ore lost to erosion at Broken Hill. It is suggested that the deposit was just breaking surface at the crest of the hill when it was discovered.

#### 6.7.2.1. *Estimate of tonnage lost from the Broken Hill deposit.*

As 3L is still largely intact, even where it outcrops within ML 11 to 13 (Figure 6.2), significant ore can only have been lost from 2L in the centre of the field. An estimate of the thickness of 2L ore lost to erosion is 15 metres. If it was 1 kilometre long and 25 metres high, and assuming a specific gravity of 4.5 (very high-grade ore), the total tonnage of ore lost from the main body of 2L (not including shear ore) would be about 1,700,000 tonnes. However, the geology of the upper levels of ML 10 to 15 also shows that 2L was only poorly represented in this area and this may be an overestimate. Furthermore, the surface and near-surface geology of ML 11 suggests that the outcrop of 2L was only 50 metres long (Figure 6.1 & 6.2a) and that the orebody did not reach surface in the other mining leases of the central Mining field.

If shear hosted and low-grade sulphide mineralisation associated with 3L, and contained within lode rocks is taken into account, then significantly more sulphide-bearing material was eroded. However, lode rocks (the likely host for low grade ore and sub-ore) are not well developed at surface in the central part of the field. It is



unlikely that the total amounts of sulphide-bearing material eroded exceeded 3 million tonnes (Figure 6.2b).

### **6.7.3. Timing of Oxidation.**

Swensson (1977) considered that two phases of oxidation affected the Broken Hill deposit, a Tertiary or pre-Tertiary event suggested to be associated with warm, humid conditions and a Pleistocene event with a related major drop in the water table associated with increasing aridity between 25000 and 16000 BP. This water table drop (up to several hundred metres) exposed more sulphide to atmospheric conditions. Some coronadite was developed below the old water table while cerussite was dissolved and re-deposited at depth. A major effect was the removal of the supergene zone (Swensson, 1977).

### **6.7.4. Exhumation of the Deposit.**

The earliest European observations of the 'broken hill' outcrops suggest that there was only a small amount of manganiferous-ironstone material lying within the scree slopes on the flanks of the hill by 1883. Contemporary descriptions suggest that large blocks of manganiferous material were just beginning to be shed from the outcrop at the hill crest (Warren, 1903). The prominent outcrop of the manganiferous material shows that it is very resistant to physical erosion. If large volumes had been shed from the outcrop, they would probably have accumulated on the slopes of the hill as scree deposits if there had been a prolonged period of erosion. As no such accumulations were observed, it seems likely that direct erosion of the lode outcrop was a relatively recent geological phenomenon.

Further evidence of the geologically recent exhumation of the coronadite-rich capping of the lode is provided by the work of Swensson (1977). He found that lead levels dropped back to background within 1000 metres of the coronadite outcrop. A much larger geochemical halo would be expected to occur around the outcrop if it had lost 60 million tonnes of ore, as suggested by Plimer (1984).

It is therefore suggested that the palaeosurface was at a level that approximated the original 1883 crest of the 'broken hill' at the time of the main weathering event. The

main mass of coronadite was formed from shallow sulphide ore and the lode rocks at this time. This level was probably about 50 metres above the present plain.

The coronadite development is not related to the current climate and weathering regime of the region as it is being exposed and eroded. The weathering and oxidation that produced the coronadite capping on the deposit only affected the shallowest part of the deposit, especially that part which lay within the plunge culmination (the 'arch') located in ML 12 and 13. This capping probably developed on the manganiferous lode rocks at or near the Tertiary palaeosurface. When erosion began to remove the surrounding weathered metasediments, this resistant cap partially protected the underlying rocks (Swensson, 1977) and was eventually exposed as the prominent outcrops that gave the hill its name.

The upper fringes of the silver-rich kaolinitic ore were exposed quite recently at surface, on the crest of the hill, by natural processes. This suggests that the coronadite cap, the kaolinisation of metasediments and the formation of the silver-rich kaolinitic ore were events that were related to the earlier phase of weathering identified by Ashley, et al., (1997).

Northeast and southwest of the plunge culmination, where the main development of 3L, 2L and lode rocks lay well below the palaeosurface, and beyond the reach of the coronadite-forming processes, only minor amounts of manganiferous lode rocks and ore were exposed on the Tertiary palaeosurface. Consequently there was no resistant capping developed on the Lode Horizon to the northeast of ML14 and to the southwest of ML11. As the later exhumation of the deposit began, the rocks to the northeast, southwest and either side of the plunge culmination were less resistant to erosion and were preferentially removed, exposing the coronadite-rich cap as a prominent outcrop.

Exhumation of the deposit by later erosion has exposed garnetiferous lode rocks as outcrops on the present surface of ML 14, ML 15 and the southwestern part of the North Mine (ML 16). These rocks show only a weak coronadite development and are only slightly weathered (Swensson, 1977). The lode rock exposures on these ML's lie approximately 45 metres topographically below the main coronadite crest of the hill. They probably lay well below the surficial weathering front which produced the coronadite-bearing cap at or near the earlier palaeosurface. It is only with later

dissection of the palaeosurface and the stripping away of the surrounding metasediments that these relatively unweathered garnetiferous lode rocks have been exposed.

It seems likely then that the already weathered and oxidised Broken Hill deposit lay within a region of low relief that now forms a palaeosurface preserved on some of the low hillcrests in the area around Broken Hill. This palaeosurface was dissected and the deposit was exhumed with the rest of the Barrier Ranges during late Pliocene-early Pleistocene low angle thrusting associated with easterly to southeasterly shortening (Gibson, 1997). The ranges form a dissected zone at the margins of an upthrust tilt block produced by a vertical displacement of 400 metres (Gibson, 1997).

## 6.8. CONCLUSIONS.

At Broken Hill, the surface expression of the deposit was mostly derived from the weathering of garnet-rich rocks and lode rocks associated with the orebodies. These still outcrop at the northeastern end of the field in the Thompson-Brown Shaft area; in the open cuts and in the Pasminco mine at the southwestern end of the field. Such outcrops contain little material that was composed of the direct weathering products of sulphide-silicate-carbonate ore/sub-ore. This observation, coupled with the other points made in the discussion above suggests that only minor amounts of ore were lost to erosion and weathering. The Broken Hill deposit was just breaking surface when it was discovered.

The geometry and nature of the surface expression and oxidised zone of the Broken Hill orebodies was controlled by the geometry and structure of the underlying garnetiferous lode rocks and mineralisation; the near-surface oxidation processes and the effects of the resultant rocks on the development of the surface topography. Where the orebodies and garnetiferous lode rocks were deeper, such as in the 2 Shaft section of North Mine or where the orebodies were deep and garnet rocks were poorly developed, such as in the South Mine and parts of the Pasminco Mine, the topography of the hill was subdued.

The greatest exposure of the Pb-Zn-Ag ore and associated garnetiferous rocks was within ML 12 to 14, where the most jagged ridge outline was found. This is the only place where 3L was directly exposed but only small tonnages of ore were eroded

because of the resilience of the ironstone-coronadite cap and the garnetiferous lode rocks. The point at which the deposit was first exposed corresponds to the plunge reversal (the arch) in the centre of the field.

Some of the richest silver and lead ores in the oxidised zone at Broken Hill were hosted in leached, weathered and iron-manganese impregnated metasediments and lode rocks. There is little evidence for true gossan material in the outcrop and near-surface oxidised zone. Gossanous material was developed only at depths greater than 50m.

Little ore has been lost from the Broken Hill deposit, so the full original extent of this giant deposit can be defined. Its regional geochemical signature is not one that has been produced by the dispersal of 60 million tonnes of ore-grade sulphide-bearing rocks. The surface expression of the Broken Hill deposit was very small and poorly mineralised in relation to its size and richness, so the failure of early prospectors to recognise its potential is understandable. It is worth considering that if erosion had removed 50 metres less overburden, the Broken Hill deposit may not have outcropped in any significant way.

These results are considered to have exploration implications in the district because other very large deposits may be only weakly exposed at surface and because exploration for the 'lost' ore of the Broken Hill deposit would be fruitless. These findings are also important to ore deposit researchers because they show that the entire Broken Hill ore system is preserved. Key components of the mineralised system have not been eroded away. So the geology of all components of the mineralised system can be studied, and the geological architecture of the entire mineralised environment can theoretically be reconstructed from the available mining and exploration data.

**Figure 6.3** Ore type & mineralogical zones identified in the oxidised zone of the Broken Hill orebodies by various authors.

JAMIESON & HOWELL (1893)			
Ore Type	Location	Mineralogy	Grade
Oxides of Fe & Mn	Formed capping of lode & to 91m & some to 122 m		22-160 oz Ag/t
Carbonate of lead	Most extensive ore type below capping. Very rare at surface	Cerussite	10-50 % Pb 7-100 oz Ag/ton
Kaolin	As masses below ironstone capping	Ag usually metallic or as chloride, iodide, chloro-bromide, or bromide, +- cerussite	12-700 oz Ag / ton
Carbonate & oxide of copper	Found in a horizontal seam within the carbonate of lead & kaolin orebodies	Contained Pb in the form of silicates & carbonate, often occurred with massive silver chloride & native Cu	30-200oz Ag/ton
Garnet rock		Aggregate of small crystals of Mn-Fe garnet	8-70oz Ag/ton, minor Pb
Sulphide ore		Sulphides of lead & zinc 30% silica & garnet	7-80 oz Ag, 26 % Pb, 21% Zn / ton
JAQUET (1894)			
Ore Type	Location	Mineralogy	Grade
Manganiferous Iron Ore	Surface capping of lode, formed the prominent ridge crests		
Dry High Grade Ore		Kaolin +/- garnet & quartz. Ag in bromian chlorargyrite as thin "seams" in kaolin	30 oz to 300 oz Ag / ton, 5 % Pb
Carbonate of Lead Ore,		Loose aggregate of cerussite crystals, "quartzo-aluminous gangue" & Mn Fe oxide	5 oz - 80 oz Ag, 20 - 60% Pb /ton
Dry Low Grade Ore		Smaller cerussite % & a larger proportion of gangue than Dry High Grade Ore	
Ore		Mix of carbonate of lead & dry high grade ores	
Sulphide Ore		sphalerite, galena, silicate, carbonate	
PLIMER (1984)			
Zone Type	Location	Mineralogy	Grade
<i>only major minerals listed</i>			
Oxide Zone:		Coronadite, quartz, goethite, 'limonite';	
Oxidation Collapse Zone:		Coronadite, quartz, goethite, 'limonite', cerussite	
Phosphate Zone:		Pyromorphite, quartz, coronadite, 'limonite', cerussite	
Complex Zone:		'Limonite', cerussite, coronadite, quartz;	
Carbonate Zone:		Cerussite, anglesite, 'limonite', quartz;	
Anglesite Zone:		Cerussite, anglesite, quartz, 'limonite', kaolinite	
Supergene Zone:		Kaolinite, quartz, halloysite.	
BIRCH & VAN DER HEYDEN (1997)			
Kintore Open Cut		Block 14 Open Cut	
<ul style="list-style-type: none"> <li>Silver halide ore /mimetite zone;</li> <li>Massive coronadite-quartz zone</li> <li>Dolomite in massive coronadite;</li> <li>Smithsonite zone</li> <li>Cerussite zone</li> <li>Sulphide ore</li> </ul>		<ul style="list-style-type: none"> <li>Massive coronadite zone</li> <li>Massive cerussite zone</li> <li>Sulphate-cerussite zone</li> <li>Smithsonite zone</li> <li>Sulphide zone.</li> </ul>	

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## CHAPTER 7: CONCLUSIONS

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### 7.1. INTRODUCTION.

The purpose of this research project was to "*gain a deeper understanding of the complex BHT style of mineralisation through a comprehensive reassessment of the geology of the type example*". Specific aims of the study, listed in Chapter 1 (section 1.3.1) and reproduced below, have been addressed in the preceding chapters, in the following order:

1. To describe the geology of the orebodies and near-ore environment of the +8.5 kilometre long Broken Hill Zn-Pb-Ag deposit (Chapter 4),
2. To synthesise a single coherent model of the structural evolution of the Broken Hill Pb-Zn-Ag deposit from the information preserved in the fabric of the orebodies and their wall rocks (Chapter 5),
3. To describe the sequence of structural and metamorphic events which produced the current form of the deposit, and to record the textural, mineralogical and geometrical changes that are related to each phase of its deformational history (Chapter 5 & Chapter 6), and
4. To develop a model of the pre-deformational form of the deposit and to suggest a depositional mechanism for the orebodies and their wall rocks (Chapter 4 & this chapter).

The evidence presented in Chapters 4 and 5 strongly supports the interpretation that the sulphide-silicate-carbonate rocks of the Broken Hill (BH) mineralised system, and companion lithologies, preserve an architecture that was present very early in the geological history of the Willyama Supergroup. Despite several phases of deformation, the primary architecture of the mineralised system remains largely intact, and *in situ*, relative to the encompassing Mine Sequence. As was shown in Chapter 6, very little of the system has been lost to recent erosion and so it can be 'seen' in its entirety, with the exception of the poorly explored, shear-dislocated northeastern extension that lies at depth, beyond the Western Shear Zone.

The majority of the evidence preserved by the rocks of the mineralised system and host sequence suggests that the orebodies are syngenetic. It is possible that there were smaller, localised components of diagenetic and/or replacement mineralisation. The degree to which the latter processes contributed to the present form of the BH

mineralised system is difficult to investigate, because of the complexities of metamorphism, but it is considered small. Further detailed work may reveal their effects. The assumption that the BH deposit is largely syngenetic will underlie the discussion of the nature of the mineralised system that is presented in section 7.3.

## 7.2. SUMMARY OF THE STRUCTURAL HISTORY OF THE BROKEN HILL MINERALISED SYSTEM.

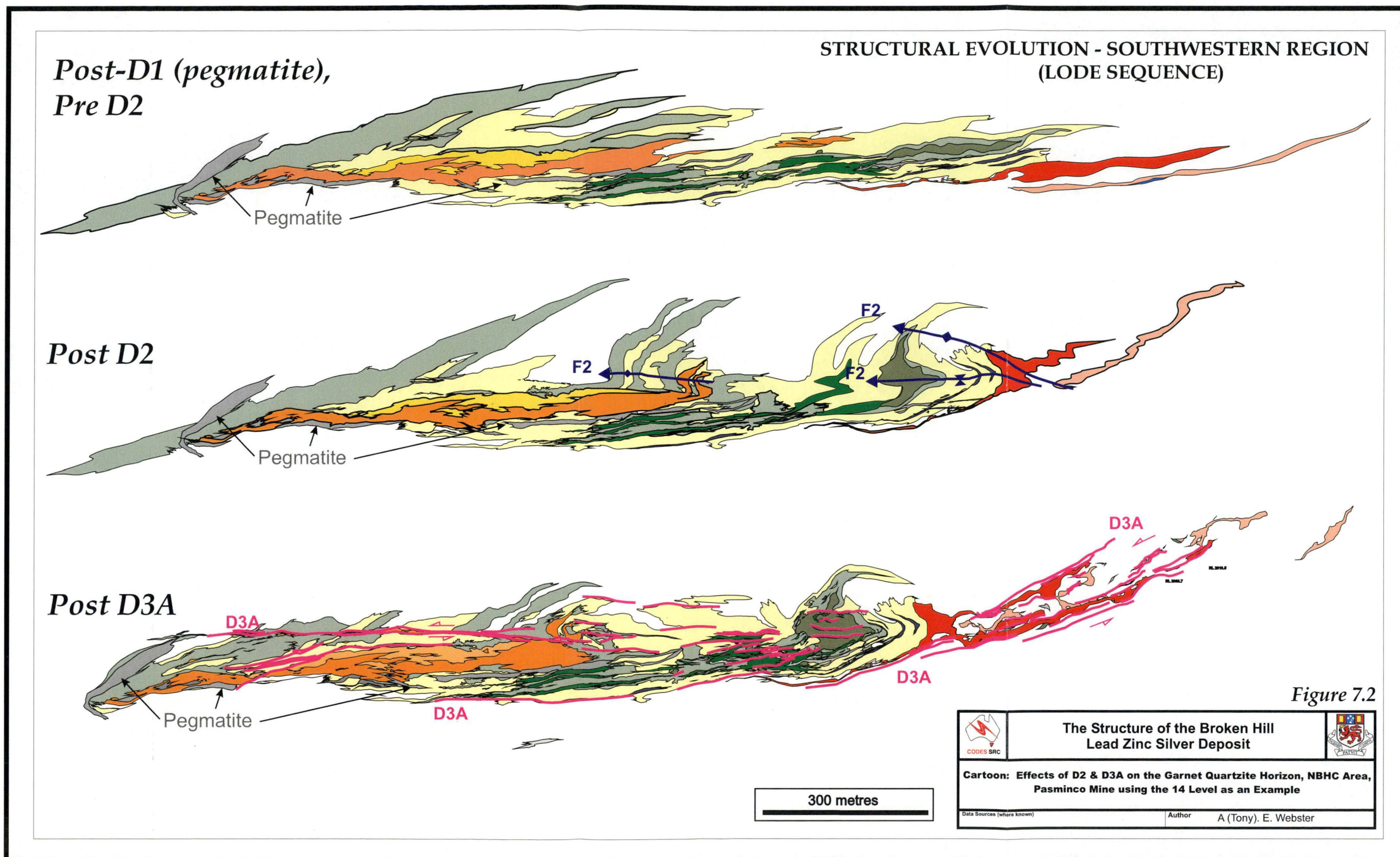
The structural history of the BH mineralised system and Mine Sequence is a clear progression of four stages (D1 to D3, followed by D4), which coincided with two distinct phases of regional metamorphism; M1 (D1-D3) and M2 (D4) (Figure 7.1). The main features of D1 to D4 are summarised in Figures 5.4 (D1), 5.8 (D2), 5.23 (D3A), 5.24 (D3B) and 5.29 (D4). Despite local complexities, and many local variations in the manifestation of each structural event (Figures 7.2 to 7.7), the structure of the mineralised system is relatively simple. Only in some regions of the mining field, where overprinting relationships or local complexities are observed, is the structure truly complicated. The four deformations recognised during this study can be correlated with the regional events of Laing et al., (1978), and those of Webster (1994a) (Figure 7.1).

*Figure 7.1. Table comparing the main structural events identified during this study, with those of previous workers. Refer to Figures 5.4, 5.8, 5.23 & 5.29 for details of each event.*

	This study	Laing et al (1978)	Webster (1994) (SW end of field)	Features in ore identified during this study
OLARIAN (M1)	D1	D1	pre-G1	Lode Pegmatite intrusion /S1, Grainsize annealing.
	D2/D3A	D2	G1/G2A	Tight-isoclinal folding, S2 (ore & wall rocks), initiation of early retrograde shearing High-grade attenuation / metasomatism, transposition & local F3 folds/S3
	D3B	D3	G2B	Biotite-muscovite shear zones Minor folds in shear zones
DELAMERIAN (M2)	D4A	F4?	G2C	Fault systems & localised high temperature hydrothermal activity (alteration of ore & wall rocks) Dolerite intrusion into orebodies & then dismembered & altered
	D4B		G2C	Late, brittle chloritic faulting & milling of ore

The first significant event to affect the BH mines area was D1, which has left little effect in the orebodies, companion lithologies or the surrounding volcano-sedimentary





**Figure 7.2.** Cartoon showing the sequence of structural events (predominantly D2 and D3A) that have produced the current geometry of the Lode Sequence (particularly the Garnet Quartzite Horizon) in the NBHC Area of the Pasmaico Mine. The 14 Level area is depicted in this example.

sequence. It is mostly manifested as a weak, bedding parallel S1 sillimanite-biotite foliation and variable development of bedding/S1 parallel, to weakly transgressive, pegmatite dykes and quartzofeldspathic melt segregations. Pegmatite intruded the orebodies and the Lode Sequence at the southwestern end of the mining field and are mildly transgressive of the stratigraphy (Figure 7.2). In the northeastern part of the field, larger stratabound dykes and melt segregations were formed at lithological contacts within clastic metasediments and adjacent to quartzofeldspathic gneiss units. Within the orebodies, the banded fabric of the sulphide-silicate-carbonate rocks was annealed.

D2 was predominantly a folding event, characterised within the Mine Sequence, in the mines area, by an asymmetric set of south verging macroscopic and mesoscopic F2 folds with variable style (Figures 7.2b; 7.3b; 7.4b; 7.5b; 7.6a and 7.7b). F2 folds in the orebodies are parasitic, lying on the northern limb of a major regional F2 antiform located south of the mining field; the Airport Antiform. This structure has previously been interpreted to be a synform (the "Broken Hill Synform") by workers such as Andrews (1922) and Laing et al., (1978).

D2 folding in the mining field area was most intense in the region northeast of the British Mine, and was associated with extensive transposition and differentiation (Figures 7.6a and 7.7b). F2 folds in this region were developed at all scales, from macroscopic structures, to parasitic folds of wavelengths less than 20cm, and were associated with the development of a galena-defined S2 fabric in the orebodies. The S2 fabric in ore is not observed in other regions of the field. To the southwest, and particularly in the South and Pasminco Mines, folding was less intense, F2 folds were more cylindrical, and pre-D2 features of the orebodies were more conspicuously preserved; particularly within the Lode Sequence (Figures 7.2b; 7.3b; 7.4b; 7.5b). In the Southwestern Domain, in the Pasminco Mine, F2 folds were associated with the formation of silicate-sulphide veins and stockworks formed within particular horizons, particularly the Garnet Quartzite Horizon, and in the massive rhodonite zones within 2L and ALL. Massive rhodonite layers within 2L were dismembered during D2 (Webster 1993; 1994a).

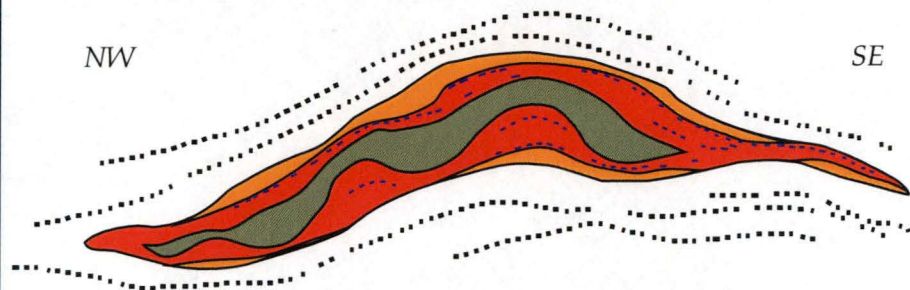
In the generally accepted structural model of the mining field (Laing et al., 1978), the Hangingwall Succession is considered to be a structural repeat of the Footwall



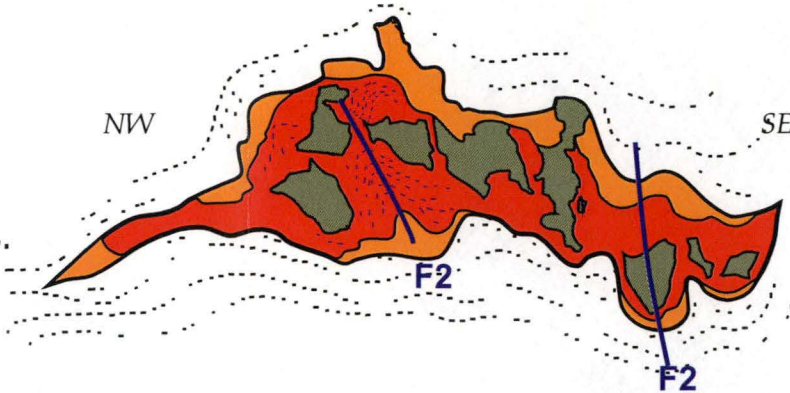
STRUCTURAL EVOLUTION - SOUTHWESTERN REGION  
(2 IENS IN THE NBHC AREA OF PASMINCO MINE)

*Pre-D1*

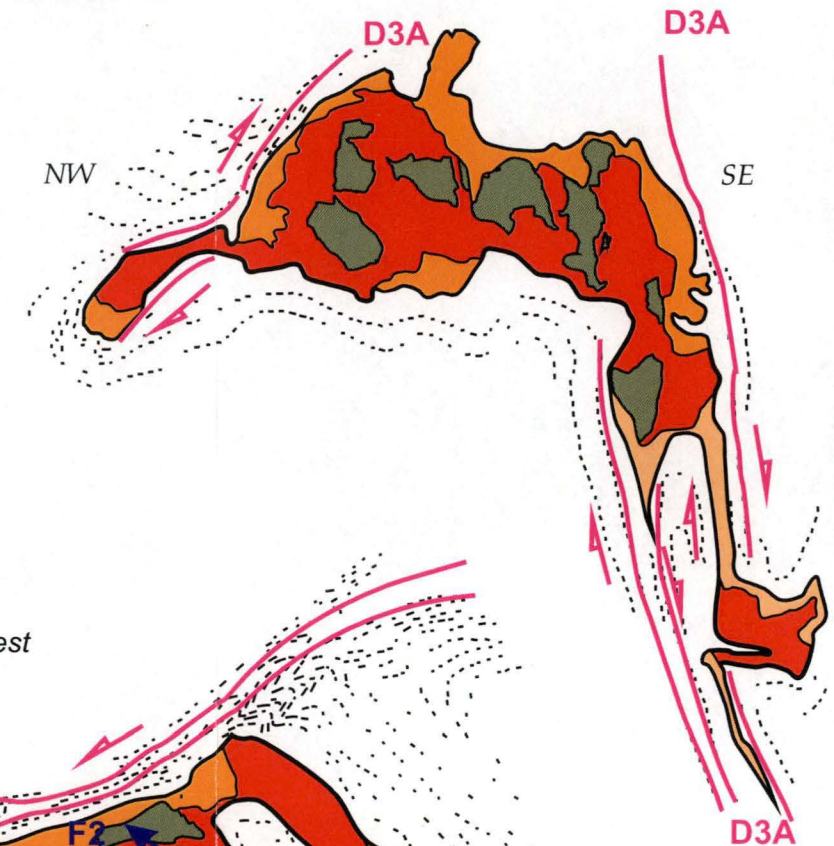
Cross Section View



*Post D2*



*Post D3A*



Plan view

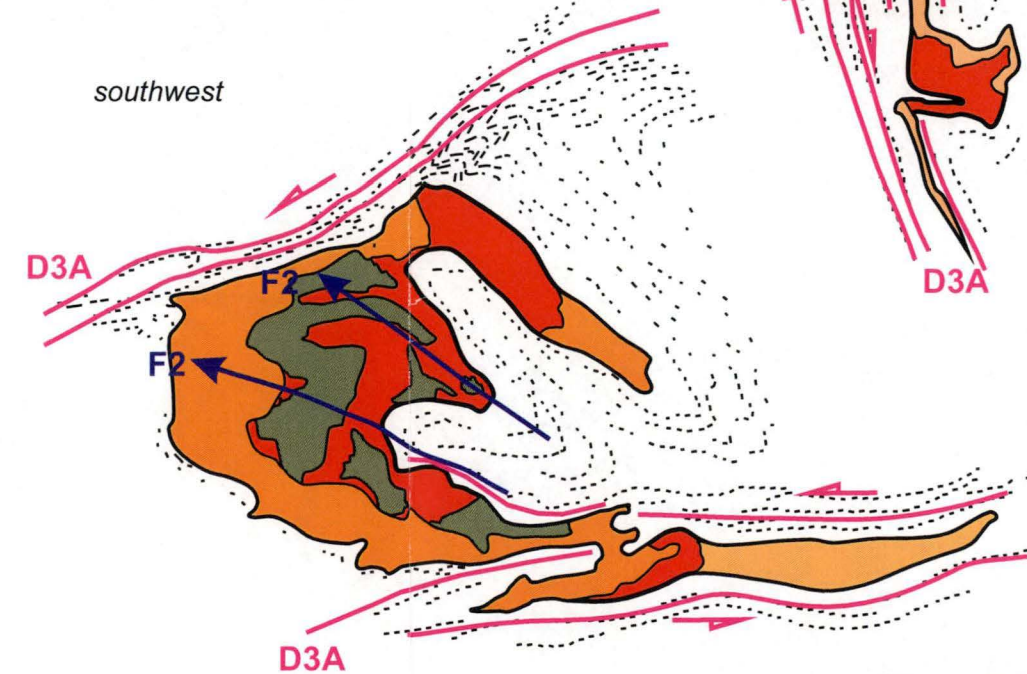
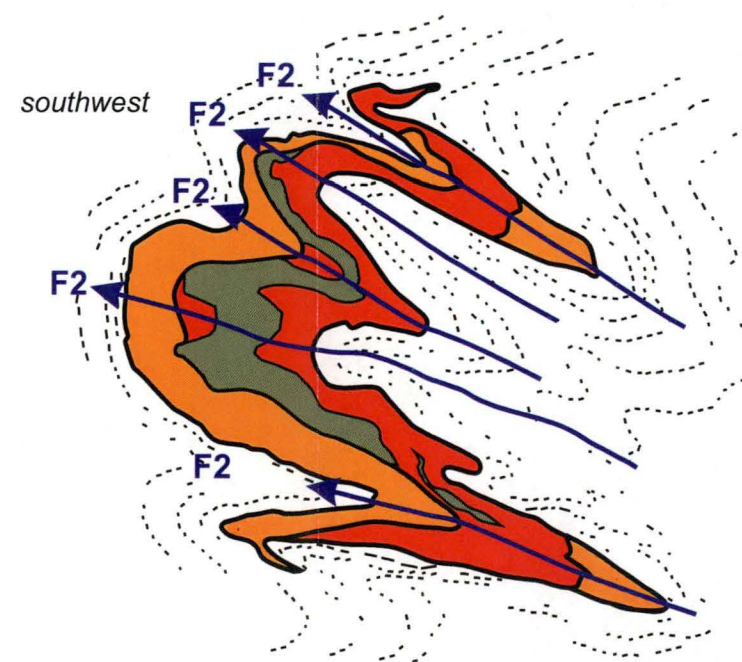
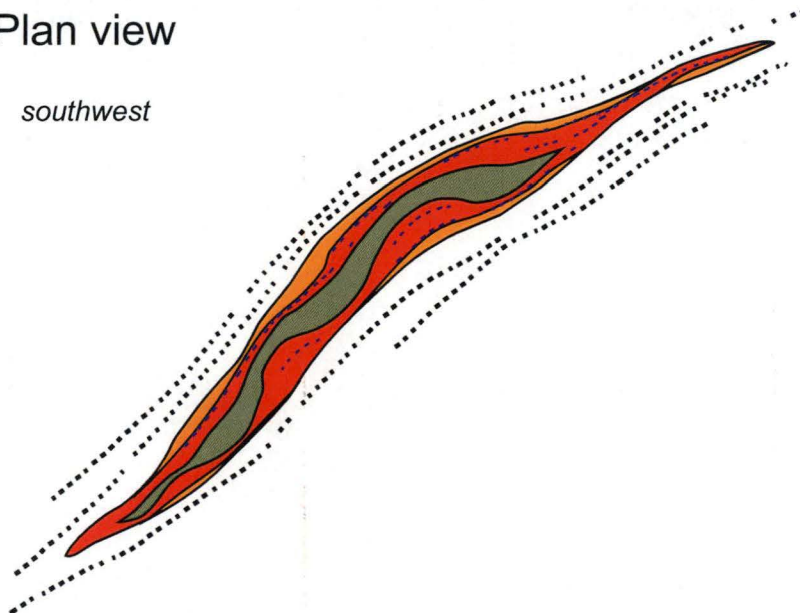




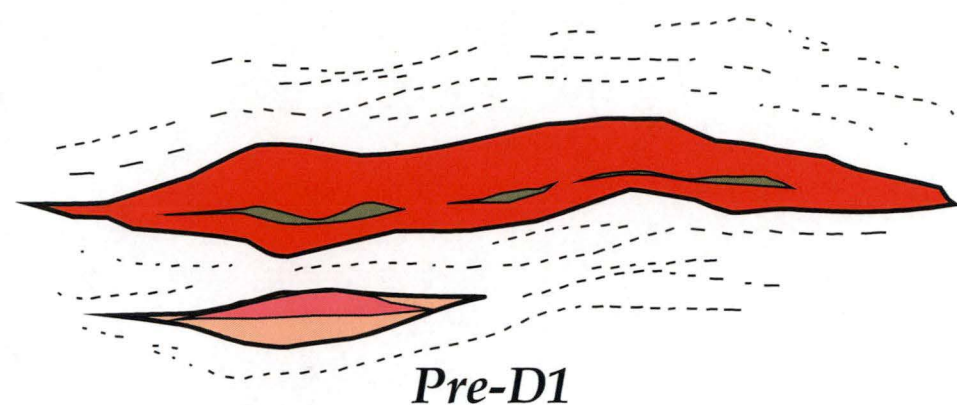
Figure 7.3

 CODES SRC	The Structure of the Broken Hill Lead Zinc Silver Deposit		
Effects of D2 & D3A on 2 & 3 Lens, NBHC Area, Pasminco Mine using the 20 Level (approx) & Stope Section 15 as Examples			
Data Sources (where known)	Modified after Webster (1994a)	Author	A (Tony). E. Webster

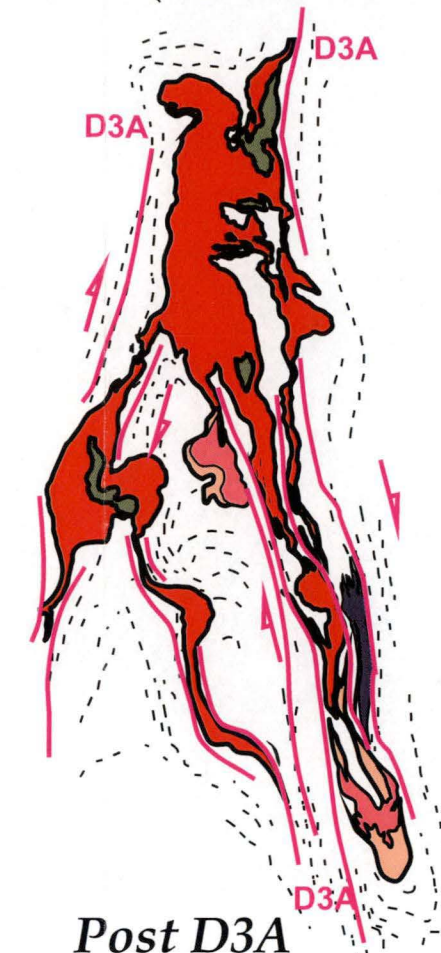
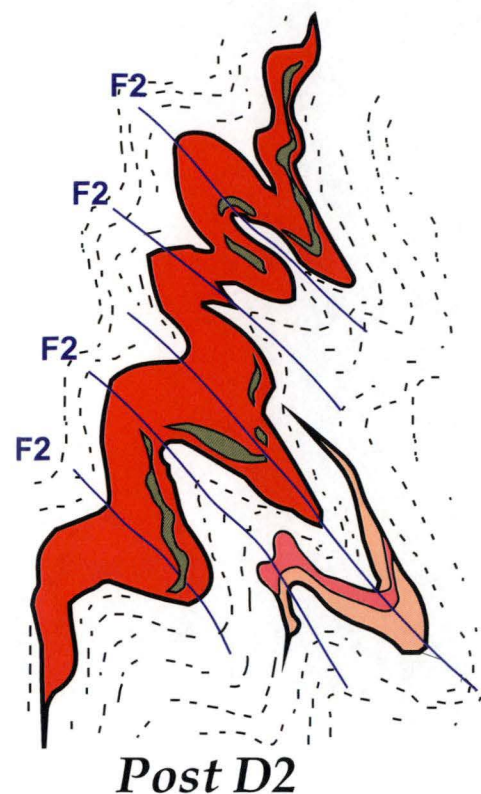
**Figure 7.3.** Cartoon showing the sequence of structural events (predominantly D2 and D3A) that have produced the current geometry of 2 Lens in the NBHC Area of the Pasminco Mine. The 20 Level SILL (approximately) and stope section 15 are depicted in this example. Refer to standard geological legend. Modified after Webster (1994a).



## Cross section view



## STRUCTURAL EVOLUTION - SOUTHWESTERN REGION (ZC AREA OF PASMINCO MINE)



Only 2 Lens, 3 Lens & part of 1 Lens Lower shown

## Plan view

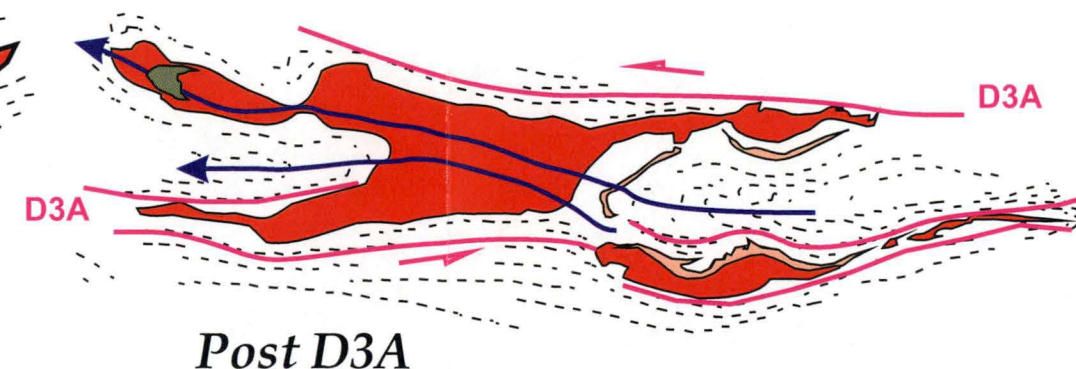
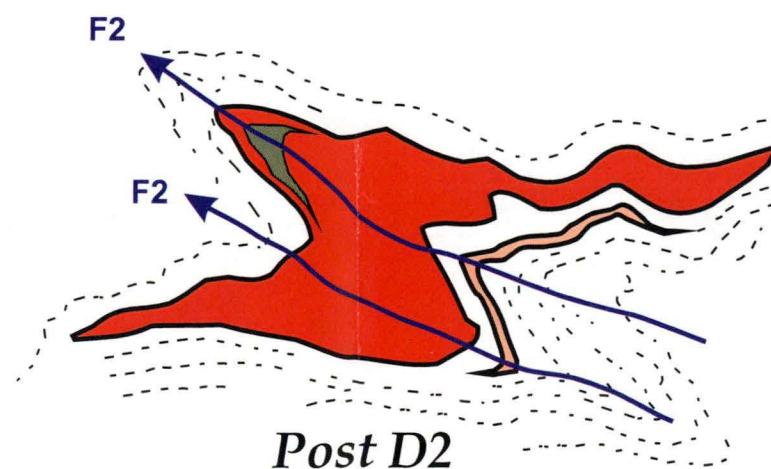
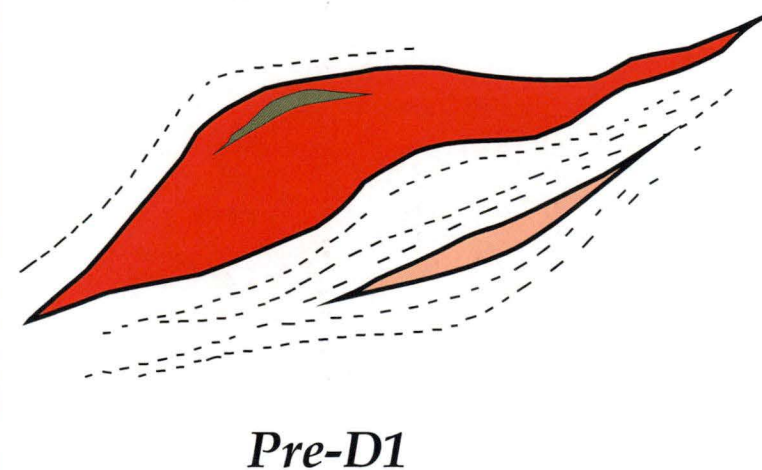


Figure 7.4

	<p>The Structure of the Broken Hill Lead Zinc Silver Deposit</p>	
<p>Effects of D2 &amp; D3A on 2 &amp; 3 Lens, ZC Area, Pasminco Mine using the 16 Level &amp; Cross Section 26 as Examples</p>		
<p>Data Sources (where known)</p>	<p>modified after Webster (1994a)</p>	<p>Author A (Tony). E. Webster</p>

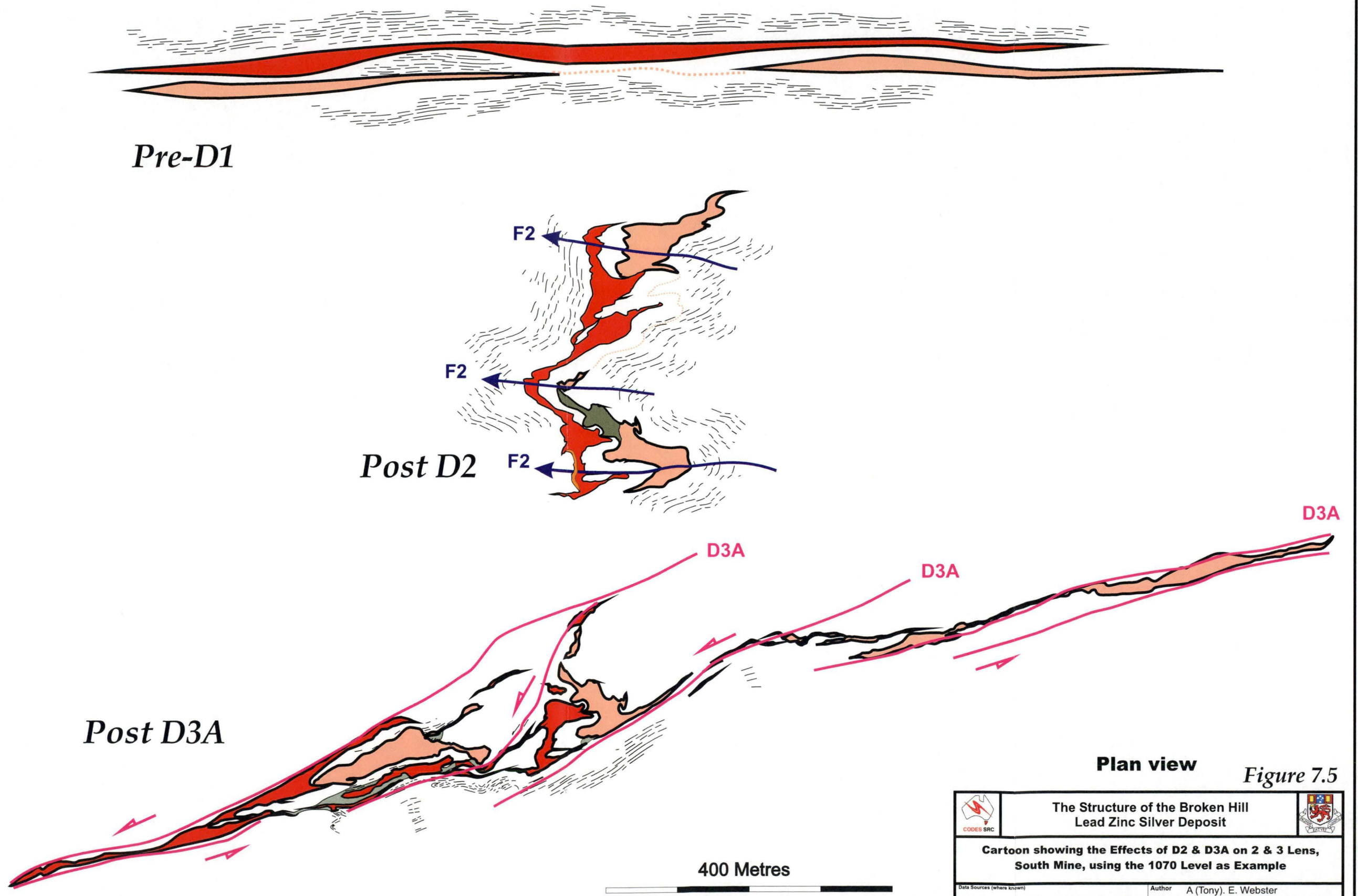
**Figure 7.4.** Cartoon showing the sequence of structural events (predominantly D2 and D3A) that have produced the current geometry of 2 Lens and 3 Lens in the ZC Area of the Pasminco Mine. The 16 Level (approximately) and cross section 26 are depicted in this example. Refer to standard geological legend. Modified after Webster (1994a).

Succession; requiring a F2 "Broken Hill Antiform" in a position in the footwall of the orebodies to produce the repetition. However, the structural repeat model does not stand up to close scrutiny. As was discussed in section 4.6 and Chapter 5, the majority of folds that affect the orebody geometry are F2 in age (Webster 1993; 1994a), whereas Laing et al., (1978) interpret them to be F3, and to refold the F2 "Broken Hill Antiform". There is no 'room' in the underwall zone of the Footwall Succession to accommodate the "Broken Hill Antiform" beneath the orebodies. The minor marker units in this area, such as calc-silicate horizons, amphibolites, 'banded-iron formations' and magnetic pelites, are not repeated, truncated or attenuated, nor do they exhibit a symmetrical distribution (see section 4.3.6). There are also significant differences between key marker units in the Hangingwall Succession and the Footwall Succession. Neither is there any observable evidence of a D2 "slide" occupying the F2 antiform position in the footwall rocks, where exposed in the workings. Instead, there is a continuous, unbroken stratigraphic sequence from the Footwall Quartzofeldspathic Gneiss to the Hangingwall Quartzofeldspathic Gneiss (see Chapter 4).

The demarcation between D2 and D3A is difficult to define and the two events are considered to be transitional. It is probable that all F2 folding included some degree of high-grade shearing and localised transposition, particularly in fold limbs and at the boundaries of large masses of more competent lithologies. This interpretation is based on the observation that there is usually a close association between the limbs of F2 folds and D3A shearing, and because D2 and D3A deformations produced texturally different but mineralogically similar fabrics in the orebodies. D3A shears were initiated during F2 folding and then became the predominant style of deformation in the mineralised system.

The effects of D3A were unevenly distributed throughout the mining field and it had its greatest effects within the British-Junction and North-eastern Regions (Figure 7.6c). In this part of the field, the Thompson Shear produced a 250-300 metre offset of 2L and 3L, strongly attenuating the orebodies and suppressing the F2 folded geometry. A similar style of high grade D3A shearing caused the attenuation of 3L and 2L and the dislocation of the Fitzpatrick Orebody from the main orebodies below the 30 Level of North Mine. The dislocation of the Fitzpatrick Orebody pre-dates the development of the more obvious quartz-muscovite-biotite fabric that is associated with the D3B Globe-Vauxhall Shear system. D3A shears were also a major influence on orebody





**Figure 7.5.** Cartoon showing the sequence of structural events (predominantly D2 and D3A) that have produced the current geometry of 2 Lens and 3 Lens in the South Mine. It is possible that in this region of the mining field, 3 Lens was comprised of two separate lenses. The 1070 Level (approximately) is depicted in this example. Refer to standard geological legend.

geometries in the lowest levels of South Mine and the Pasminco Mine, where some F2 folds were almost destroyed by shearing (Figure 7.5c). D3A shears were more localised within the Lode Sequence in the Pasminco Mine, forming relatively narrow shear zones, such as the B Lode Shear (Figure 7.2).

D3B was a continuation of D3A and is characterised by the development of a series of biotite-muscovite-quartz shear zones throughout the mining field area. Most D3B shear planes are localised within, or closely associated with, earlier D3A structures but separate developments are also seen. D3B shears were the first type of retrograde shear to be recognised in the BH district (e.g. Andrews, 1922; Vernon and Ransom, 1971) and are the most easily distinguished. The northeastern region of the mining field is most severely affected by D3B shearing and it produces the important Globe-Vauxhall-Western Shear System, which is prominent along the northern periphery of the mining field.

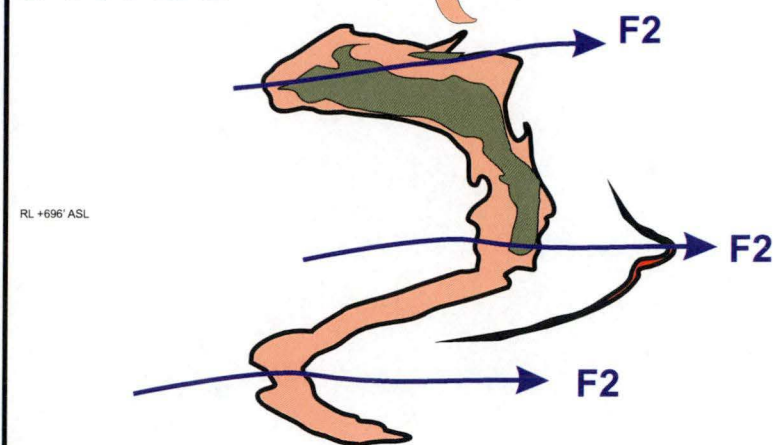
M2 affected the orebodies during the Delamerian Orogeny and locally exceeded greenschist grade. M2 was associated with a fourth period of deformation (D4). Within the orebodies, it caused the re-activation of Olarian D3A-D3B shears and produced a generation of brittle fault systems, associated with localised belts of F4 folding. Transgressive dolerite dykes intruded the ore system in three main belts and were subsequently dismembered and weakly garnet-altered within ore. D4 had particularly widespread effects in the northeastern part of the mines area, being mainly manifested as brittle-ductile to brittle deformation that is most commonly represented by the development of extensive fault, joint and fracture systems. D4 structural features overprint Olarian structures within the orebodies.

There were at least two distinct phases in D4 (D4A and D4B). D4A was a relatively high-grade phase that reached lower amphibolite grade in places and locally higher grades in some faults. It was associated with hydrothermal activity, dolerite intrusion and local folding. D4A faults were associated with localised ductile deformation, in the form of F4 folds, and caused the major reversal in F2 plunges in the central mining field (Figures 7.6b and 7.7d). Within the mines area, the most significant belt of D4A deformation is the British Fault system, a multiple planed, north striking zone that traverses the mines area in the British Junction Region of the field.



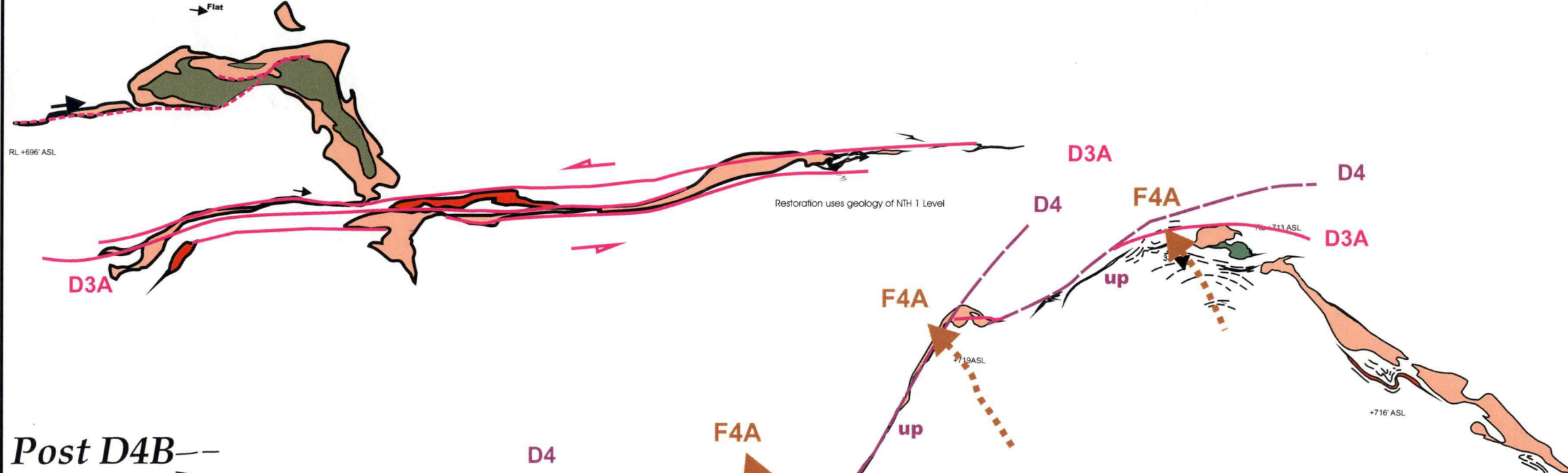
Post D2

# STRUCTURAL EVOLUTION - BRITISH-JUNCTION REGION

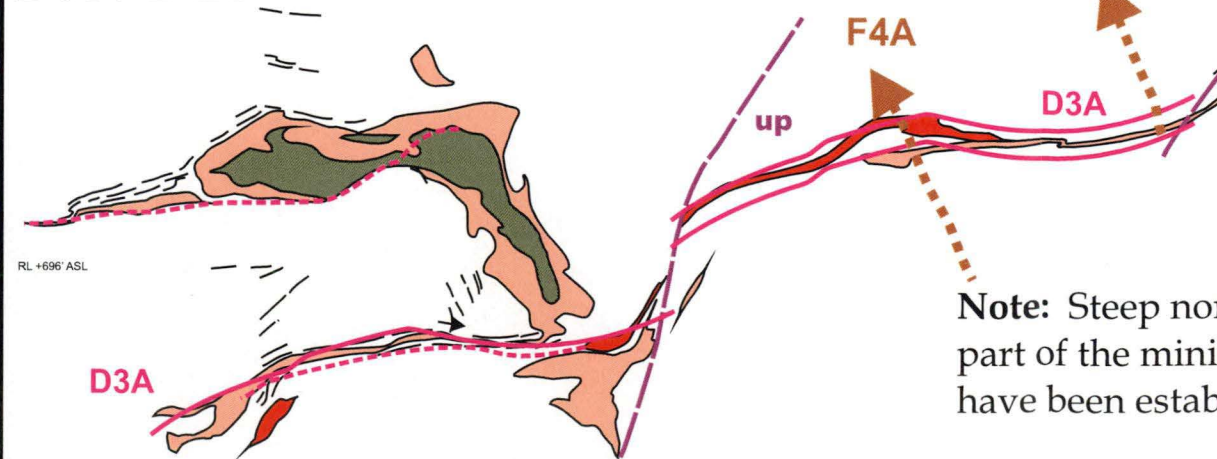


Note: Post D2 and post D3, this part of the mining field would have been shallow southwest plunging

Post D3A



Post D4B



Note: Steep northeast plunge of this part of the mining field would only have been established post D4A.

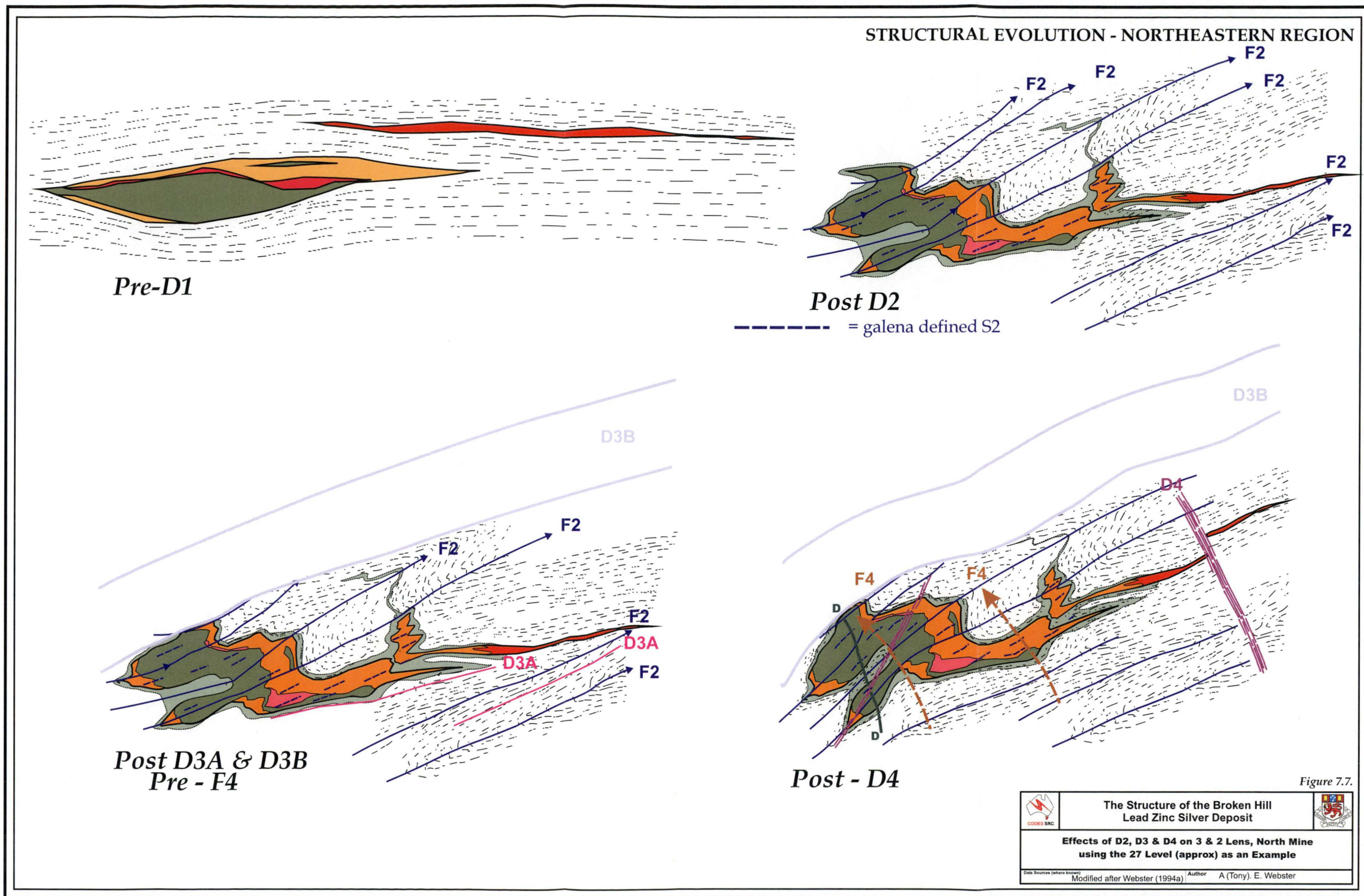
Plan view

Figure 7.6

	<p>The Structure of the Broken Hill Lead Zinc Silver Deposit</p>	
<p>Cartoon: Showing the Effects of D2, D3A &amp; D4 in 3 &amp; 2 Lens in the British Mine area.</p>	<p>Author A (Tony). E. Webster</p>	

Figure 7.6. Cartoon showing the sequence of structural events (D2, D3A and D4) that have produced the current geometry of 3 Lens (pink) and 2 Lens (red) in the British Mine, in the British-Junction region of the deposit. Refer to standard geological legend.





**Figure 7.7.** Cartoon showing the sequence of structural events (D2, D3 and D4) that have produced the current geometry of 2 Lens and 3 Lens in North Mine. The 27 Level (approximately) is depicted in this example. Refer to standard geological legend.

F4 folds were closely associated with complex D4A fault zones, such as the British Fault System, and refold the main orebodies (Figures 7.6b and 7.7d). Pegmatite veins developed in F4 hinges (e.g. Laing et al., 1978). Mechanical sulphide mobilisation dismembered dolerite dykes within 2L and 3L (e.g. Webster, 1996b). Hydrothermal activity along D4 faults produced alteration within mineralisation, including sulphide mobilisation and impregnation on the margins of the dykes. It was also associated with the formation of hydraulic breccias, laminated vein systems, tension vein systems, and wall rock alteration in gangue, and in localised areas around fault and vein margins (e.g. 2L and amphibolite adjacent to the Consols Lode).

D4B was a subsequent phase of relatively low temperature brittle deformation, which was possibly a distinct reactivation event. It produced widespread, relatively minor, joint, fault and fracture systems throughout the mining field.

### **7.3. INFERENCES ABOUT THE BROKEN HILL DEPOSITIONAL SYSTEM.**

#### **7.3.1. Introduction.**

Empirical evidence allows inferences to be made about the processes that contributed to the formation of the deposit and the changes that took place in that system as the orebodies and companion rocks were laid down. Despite the fact that the geometry and mineralogy of the deposit have been modified during four deformations and two regional metamorphic episodes, the increased understanding resulting from the present study allows the effects of these events to be 'removed' and the remaining early features to be identified. By reconstructing the ore environment, a considerable amount can now be said about features of the depositional system that formed the orebodies. The following discussion is focussed on what the empirical field evidence reveals about the mineralising system that formed the BH deposit (Chapters 4 and 5).

#### **7.3.2. Manganese Distribution.**

Manganese is a widespread component of the rocks associated with the BH mineralised system, where it is most apparent as a component of variable densities of disseminated, fine to coarse-grained spessartine garnet. Manganese is also an

important constituent of the orebodies, particularly of the gangue minerals within them.

Garnet quartzite and its altered derivatives, such as 'garnet sandstone', are the most distinctive manganese-rich rock of the ore environment, forming a key component of the Lode Sequence. Garnet quartzite is known to occur beyond the mining field, but only as part of small and relatively insignificant mineralised zones. Layers, bands and zones of rhodonite, and the products of its metamorphic alteration (e.g. bustamite and hedenbergite) are the most distinctive manganese-bearing rock within ore, and form marker horizons in ALL, 2L and 3L (e.g. Webster, 1994a). Rhodonite occurrences in the Willyama Supergroup are mostly restricted to the main orebodies, with only small occurrences known elsewhere in the Broken Hill Group (e.g. Barnes, 1988). Garnet quartzite and rhodonite are therefore distinctive manganese-bearing components of the main BH mineralised system.

#### 7.3.2.1. *Garnet Quartzite.*

The garnet quartzite that forms the bulk of the Garnet Quartzite Horizon (GQH) is fine-grained and massive to finely laminated in texture. Layering within garnet quartzite is concordant with orebody margins, the banded fabric of the ore lenses, and with the GQH contacts. Laminated and banded garnet quartzite is intruded by D1 pegmatitic segregations and dykes, and is extensively invaded by syn-D2 and syn-D3 sulphide-silicate veins. The greater part of the fabric is therefore interpreted to be pre-D1, and probably a depositional layering (S0). The fine layering gives garnet quartzite a superficial resemblance to chemical sediments, such as banded iron formation, but the richness in quartz, and the features that strongly resemble cross bedding observed within it, suggest it was probably not formed as a chemical sediment but as an aluminium and manganese-enriched clastic sediment.

The majority of the lesser sulphide lenses of the BH mineralised system are associated with the GQH, they are all of the siliceous type (see Chapter 4), and there is probably a close genetic relationship between the formation of the garnet quartzite precursor and the siliceous style of mineralisation (see section 4.8). A Lode Lower marks the onset of the deposition of the GQH, while BL lies at the stratigraphic position where significant garnet quartzite deposition ceased. These orebodies, the largest unequivocal Siliceous



orebodies, were deposited at the upper and lower contacts of the GQH. Smaller ore lenses, such as ALU, formed within the horizon as distinct layers. All sulphide lenses have sharp contacts with garnet quartzite, even in locations where they are completely enclosed by it.

Despite the close association between ore lenses and the GQH, no orebodies contain internal layers of garnet quartzite, which is only present in the ore as clasts and fragments in syntectonic mobilised sulphide zones. Beyond the boundaries of the ore lenses, the only mineralisation that is observed within garnet quartzite is D2/D3 mobilised sulphides, usually as silicate-sulphide veins and stockworks. These observations suggest that, at the time it was first formed, the precursor of the garnet quartzite was not mineralised, despite its intimate association with several stratiform orebodies. At ore lens scales, the deposition of the manganiferous garnet quartzite precursor was antipathetic to sulphide deposition. Garnet quartzite can host an ore lens but it is not mineralised in itself.

The geometry of the GQH is that of a an elongate lens comprised of a series of conformable, stacked layers that are intercalated with the surrounding Lode Sequence clastic metasediments. The stacked layers are lenticular in cross section and elongate parallel to the long axes of the orebodies contained within the horizon. The sharp depositional contacts between ore lenses and manganiferous rocks suggest that there were rapid changes from ore deposition to manganese enriched clastic sedimentation during ore genesis. The events that deposited the base metals and their associated silica within the GQH occurred during periods of little or no deposition of manganiferous sediments.

There are only weakly developed zones of garnet quartzite associated with the Calcitic orebodies (2L, 1LU, 1LL) and the accumulation of these orebodies was not associated with the same levels of manganese-rich sediment deposition as were the Siliceous orebodies. 3L only has narrow zones of garnet quartzite along its footwall contact. If the GQH is interpreted to have formed as a wall rock alteration around mineralisation (a 'halo'), then it is an unusual one because there is no significant association of garnet quartzite with 2L and 3L, the two largest orebodies of the mining field. Neither does garnet quartzite enshroud BL, the third largest orebody in the deposit. An intense alteration halo that was associated with the deposition of the sulphide orebodies could

reasonably be expected to be best developed in association with the two largest orebodies of the mineralised system. Instead, 2L and 3L are hosted within unaltered clastic metasediments. The GQH precursor is therefore interpreted to have been laid down as a manganese-rich clastic sedimentary unit that was deposited concurrently with the smaller Siliceous orebodies and focussed at the southwestern end of the ore depositional environment (see also section 7.3.6). The sedimentary environment of deposition was probably relatively high energy.

### 7.3.2.2 *Rhodonite (manganese silicate).*

During the deposition of 3L, 2L and ALL, there were periods of manganese deposition, with a significant calcium component, which are now thick rhodonite layers within the orebodies. However, despite the position of the rhodonite-rich layers within these orebodies, they contain very little sulphide. Like the garnet quartzite, massive rhodonite layers in 2L, 3L and ALL are only mineralised by syntectonic mobilised sulphides (Webster 1993, 1994a). This observation suggests that no sulphides were deposited within the rhodonite precursor during these interludes of manganese deposition, even though they comprise an integral component of each orebody. The rhodonite layers are a further example of the antipathetic relationship between manganese deposition and base metal sulphide deposition within the ore system (see section 7.2.1.1).

3L, 2L, and ALL lie approximately adjacent to one another within the Lode Sequence. However, ALL is one of the Siliceous orebodies, hosted within the GQH, while 2L and 3L are clastic metasediment-hosted and 2L is rich in calcite. In terms of their general geology and metal content, these three orebodies are quite different. However, the presence of rhodonite in all three orebodies suggests some commonality in the depositional processes that formed them. There was continuity in the depositional mechanisms that formed the clastic metasediment hosted Calcitic orebodies and the garnet quartzite-hosted Siliceous orebodies. The deposition of the rhodonite precursor persisted through this transition.



### 7.3.3. Calcite Distribution.

Calcium carbonate is a major component of the lower BH orebodies, including 2L, 1LL, 1LU and southwestern 3L. However, calcite is mostly restricted to a very narrow stratigraphic range within the mineralised system and is very rare elsewhere in the Willyama Supergroup. Calcite is perhaps the most distinctive and unusual constituent of the BH mineralised system.

Within the Lode Sequence, calcite-bearing mineralisation was formed as a single, highly focussed phase within a relatively narrow stratigraphic range. Calcite-rich mineralisation contains the highest Pb grades of any style of mineralisation within the BH deposit and it comprises the richest ore mined. The narrow zone of calcium carbonate rich ore can be thought of as a distinct phase of the mineralising system that 'interrupted' the more general siliceous and sulphide-rich ore forming processes. These processes commenced with siliceous ore in 3L and persisted to form the upper orebodies (including BL) after calcium carbonate ceased to be generated as a significant proportion of ore.

Within 2L (and 1LU and 1LL), calcite-rich regions of the orebody may contain bands and layers of rhodonite, apatite and fluorite but excludes free quartz and massive occurrences of rhodonite. Quartz-rich zones within the ore are sharply divided from calcitic zones and contain greater proportions of sphalerite and galena. Massive rhodonite layers in southwestern 2L may contain narrow bands of calcitic ore but the two phases remain sharply demarcated.

The underwall zone of the Footwall Succession contains several rock types that are enriched in calcium relative to the surrounding clastic metasediments. This package may represent the onset of the calcium-iron-manganese enriched depositional system, which foreshadowed the onset of the unusual calcite-rich system that produced the Calcitic orebodies. It is also possible that these rocks represent some form of related footwall alteration.

#### 7.3.4. Fluorite Distribution.

Fluorite is a significant component of 2L and 3L, defining distinct layers within each orebody (e.g. Figure 4.23, 4.24). Fluorite is also present within 1LL (Gustafson et al., 1950).

A fluorite-enriched zone occurs in 3L, at the interface between the lower rhodonite zone, and the quartz-rich ore that occupies the hangingwall (e.g. Figure 7.7). Fluorite does not form a significant component of these other gangue zones and seems to have been deposited within the orebodies as a distinct horizon lying between them. The mechanism that formed the 3L sulphide orebody must have independently produced fluorite, the rhodonite precursor and quartz at successive stages of the depositional process, with little intermixing, while the sulphides were forming.

The fluorite distribution in 2L is less well understood due to relatively poor mapping and drilling coverage within the main mass of the orebody. However, where directly observed (e.g. Webster 1994a), it forms a layered zone of enrichment within banded calcitic ore and is intimately intergrown with calcite, apatite and sulphides. In this instance, fluorite seems to have been deposited as a discrete phase in the deposition of calcitic ore in 2L and is less distinct from other gangue constituents than is the case in with the layered zones in 3L.

#### 7.3.5. Primary Quartz Distribution.

The southwestern end of the BH mineralised system was the locus of the greatest accumulations of the siliceous style of mineralisation (see section 4.8), as it was for the deposition of manganese-bearing clastic sediments (GQH and B Lode Horizon), and a genetic association is probable. The observed geology suggests that the Siliceous orebodies were formed as elongate, flattened lens-shaped bodies, at particular stratigraphic levels within a thick lens of manganese-quartz dominated sediments (the GQH). It is inferred here that the sulphide ore was deposited as distinct events during the formation of the manganese-rich sediments. In the positions where the sulphides were accumulating, little or no clastic sediments were deposited.

Siliceous ore zones are a feature of all orebodies, including the calcitic 2L and 1LL (see Chapter 4) and always occur at the top (hangingwall) of each lens. The lead grade of 3L is usually much higher in the hangingwall Quartz Zone in the North Mine (Figure 4.23, 4.24). This is probably also the case in the Pasminco Mine. Visual grade estimations, face sampling data, and mapping information suggest that the Sulphide-Quartz Zone in 2L is also higher grade than the main mass of calcitic ore in these orebodies in the Pasminco and South Mines. However, grade distribution analyses are required to confirm this observation.

The siliceous zones on the upper contact of the 1 Lens orebodies show similar sulphide enrichment, relative to the main calcitic mass, as in 2L. B Lode, the largest in tonnage and highest in grade of the Siliceous orebodies, only contains quartz as a significant gangue constituent. Therefore, there is an association between high sulphide contents and quartz gangue distribution within all of the largest BH orebodies.

### **7.3.6. The System that Deposited the Broken Hill Orebodies.**

The mineralising processes that formed the huge, but highly localised and linear BH orebodies, and their companion lithologies, must have been able to generate lead and zinc sulphides, calcium carbonate, fluorine, phosphate, silica and manganese in huge quantities. These diverse constituents then had to be deposited as intimately mixed but layered components of linear sulphide bodies and manganese-rich sediments.

Sulphides seem to have remained a relatively constant component of the material deposited by the system as it developed over time. However, zinc sulphide accumulation seems to have remained at a constant weight percentage of the total volume of mineralisation deposited within each orebody, while lead diminished over time (Webster, 1994a).

The observed relationships between the orebodies, Lode Sequence units and the surrounding clastic metasediments of the Mine Sequence suggest that sulphides were deposited in abrupt events. In the narrow corridor where the orebodies were formed, accumulation of sulphides within the Mine Sequence started after a period of psammite-psammopelite deposition (the top of which is represented by the 'underwall zone' in the near-ore environment) and then abruptly ceased, with clastic

sedimentation recommencing again after the laying down of the B Lode Horizon. During the formation of the orebodies and Lode Sequence, clastic sedimentation continued beyond the margins of the narrow mineralised corridor, at time-equivalent positions within the stratigraphy. Within the Mine Sequence, 2L, and its branches (1LL and 1LU) are intercalated with clastic metasediments at the southwestern end of the deposit, in the Pasminco Mine. This is best explained by localised but rapid formation of ore lenses at a comparable rate to the deposition of the surrounding clastic sediments.

The formation of the orebodies is interpreted to be the result of pulses of sulphide mineralisation that were generated during a period of clastic sedimentation. The deposition of the mineralisation started abruptly (3L), evolving into a focussed zone in which manganese-rich sedimentation became associated with the deposition of sulphides. During the periods of sulphide generation that formed 2L and 3L, intervals of sulphide-poor manganese-calcium-silica deposition took place, which formed the rhodonite precursor within these orebodies. Following the deposition of 2L, the input of manganese to the near-ore depositional system increased, particularly in the southwestern part of the deposit, eventually forming the GQH. The sharply defined lower contacts of the GQH suggest that the onset of its accumulation was sudden. Following the formation of the B Lode Horizon, the localised manganese and sulphide input to the clastic sediments of the Mine Sequence abruptly ceased, or diminished to very low levels.

Initially, metal deposition was focussed in a 8.5km-long, restricted linear zone, hosted within clastic sediments (3L, 2L). Mineralisation then became more localised at the southwestern part of the system and became associated with manganese input into the sediments (the Garnet Quartzite Horizon). The final stages of the mineralising event were more widespread and disseminated, affecting the entire BHI region in a phenomenon that formed layers, patches and disseminations of mineralisation within both the B Lode and 4.5 Horizons, and regionally within the Lode Horizon (known from Kelly's Creek in the southwest to the Barrier Consolidated Mine in the northeast). This phase of the mineralising event left evidence throughout the Broken Hill Group. The huge volumes of lead and zinc that were deposited throughout the regionally extensive Lode Horizon (within the Hores Gneiss) are testimony to the final, widespread nature of metal deposition.

### 7.3.6.1. *Metal Deposition.*

The evidence preserved within the BH deposit suggests that the processes that deposited the base metals evolved with time, from a system that was initially rich in lead and calcium (2L, 1LL, 1LU & southwest 3L) but which evolved over time to become relatively lead-calcium depleted. Zinc deposition was coincident with lead-calcium deposition but remained at approximately constant levels throughout the evolution of the system. As a result, all orebodies have similar zinc grades but the lower orebodies are richer in lead and calcium (3L, 2L, 1LL, 1LU) (Webster 1994a). Lead and calcium deposition diminished with the onset of the formation of the GQH.

The onset of deposition of all sulphide lenses was abrupt because the contacts between orebodies and their enclosing rocks are sharp. With the exception of BL, which has a transitional upper contact with the B Lode Horizon, the deposition of each of the BH orebodies ended just as abruptly. The mechanism that generated the orebodies within the GQH was not transitional between base metal and manganese sediment formation because there are no transition zones. A similar situation prevailed with the Calcitic orebodies where clastic sedimentation ceased during sulphide-silicate-carbonate deposition. Apart from the upper contact of B Lode, the metallogenic system that produced the BH deposit did not produce any transitional zones between sulphides and wall rocks. Base metals were deposited, or they were not.

The orebodies of the BH deposit are composed of a far more complex array of minerals than just two sulphide species. The evidence preserved within the orebodies suggests that the deposition of particular sulphide species was linked to other geochemical factors, aspects of which are represented by the gangue species that are found within them. Therefore, the geochemical processes that produced the BH mineralisation also generated large volumes of calcite, fluorite, apatite and quartz, in association with manganiferous sediments, at different stages of sulphide formation, without mixing the components. This same process produced manganiferous sediments at intervals (garnet quartzite, rhodonite), without producing any sulphides.

The sequence upwards from 2L through the 1 Lens orebodies; ALL and ALU to BL shows a decline in calcium-bearing mineral assemblages, a decline in the occurrence of rhodonite horizons within ore and an increase in primary (as opposed to metasomatic)

quartz within mineralisation. The decrease in calcium carbonate and manganese deposition, and the relative increase in silica and sulphide deposition as the successive ore lenses were deposited, is interpreted to reflect an evolving mineralising system. The quartz-sulphide rich mineralisation has the highest proportion of sulphides relative to gangue of all ore types.

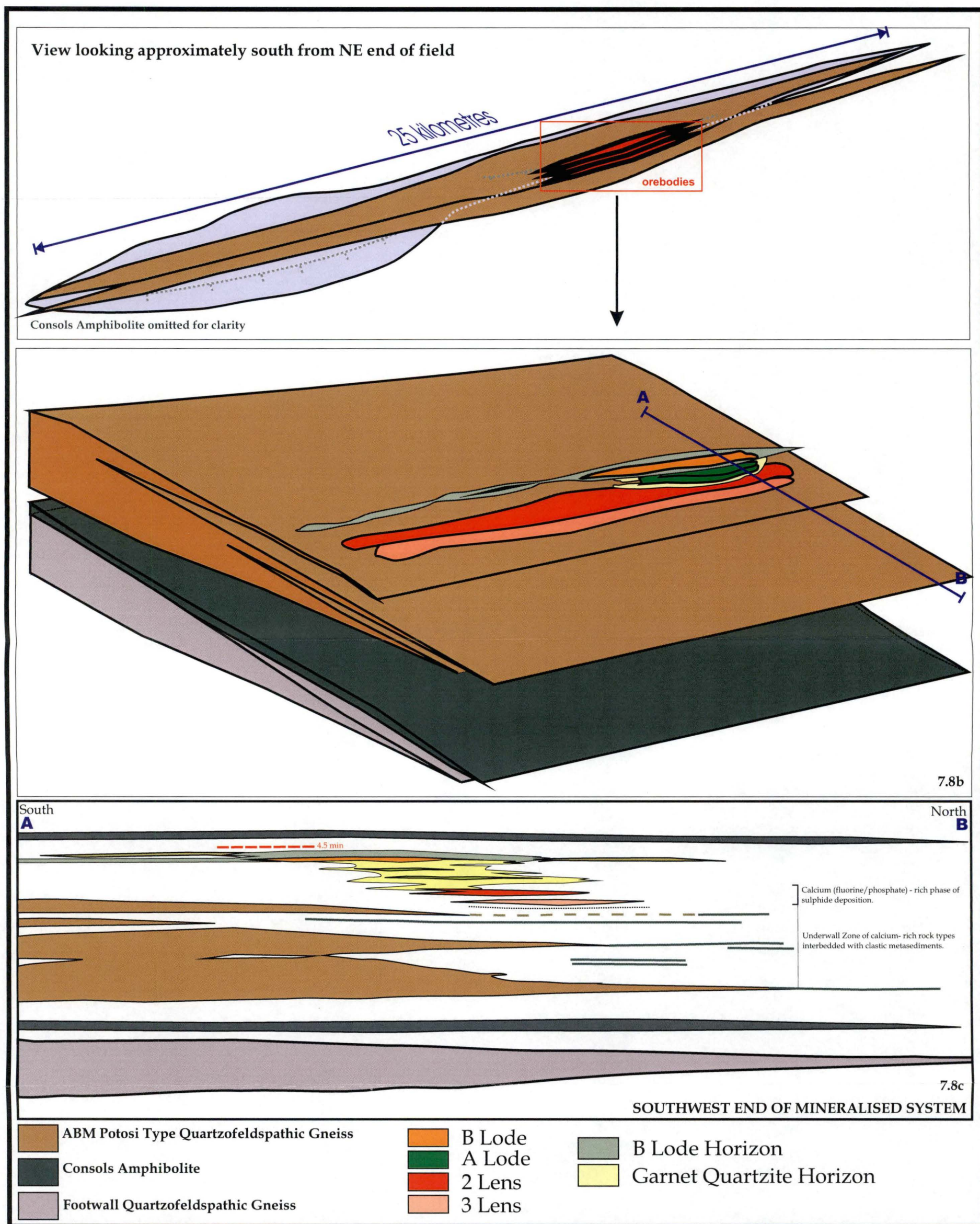
#### 7.4. GENESIS OF THE BROKEN HILL MINERALISED SYSTEM.

The empirical evidence preserved by the rocks of the BH mineralised system is compatible with the interpretation that they were formed by direct deposition from the water column of the Palaeoproterozoic ocean. The Lode Sequence formed as a linear suite of metal-rich chemical, clastic and chemically enriched clastic sediments, with sulphide layers, that were intimately intercalated with the surrounding clastic sediments. The orebodies and lode rocks are sharply demarcated from the enclosing clastic metasediments but are intimately intercalated with them. This suggests that the BH mineralised system was formed in an environment that was on the sea floor, at the sediment-water interface. The general characteristics of this environment are probably those envisioned by previous workers such as King and O'Driscoll (1953) and Laing et al., (1978) and it was probably a shallow marine environment (Haydon and McConachy 1987; Wright, 1985; Wright et al 1987; Wright et al., 1993). The formation of the deposit was indirectly associated with a volcanic or volcano-sedimentary complex that is now represented by the Footwall Quartzofeldspathic Gneiss, ABM Potosi Type Gneisses and Consols Amphibolite of the Footwall Succession (Figures 7.8).

The environment of formation could allow large accumulations of linear mound or trough-shaped chemical and clastic sediments. Such an environment may have been on a shelving shoreline, a reef-like accumulation, or a trough like depression in the ocean floor. Of these possible environments, the former two are preferred. The location of the deposit is on the flank of a bimodal volcano-sedimentary complex, which probably formed the linear, topographic element along the fringes of which the mineralisation accumulated (Figure 7.8).

The mechanism that concentrated the raw materials of the BH mineralised system is more enigmatic. Base metal sulphides accumulated in association with periods of





**Figure 7.8.** Cartoon depicting a reconstruction of the relationship between the Broken Hill mineralised system and the underlying volcano-sedimentary complex. The orebodies are located at the southwestern thinned 'tail' of the elongate and lens-shaped complex and lie parallel to its long axis. The high aspect ratio of the Lode Sequence and orebodies corresponds to that observed in the underlying volcano-sedimentary rocks, particularly the ABMPG and FQG. The blue line marked A-B marks the plane of the section shown in 7.8c.

**7.8b.** The orebodies lie within clastic metasediments on the northwestern flank of the complex, where it lenses out into the surrounding metasediments, calc-silicate horizons and thin amphibolite units. Refer also to Figure 7.8c.

**7.8c.** Shows a schematic cross section of the southwestern end of the mineralised system and shows the relationship between the location of the Lode Sequence and the thinned margins of the ABMPG, CA and FQG.



calcium carbonate, silica, fluorine, phosphate and manganese deposition, though these additional components of the orebodies were deposited in separate layers and bands within the sulphide accumulations. Each gangue type was often deposited in a layer in which it formed the predominant non-sulphide species, to the exclusion of others.

The generation of manganese was an integral part of the mineralising system and all of the mineral constituents of the orebodies were formed in spatial association with manganese deposition, despite the fact that this was antipathetic to base metal deposition at a local scale. The latter phase of base metal deposition at BH was coeval with a much more extensive (basin wide?) deposition of manganiferous sediments (the distal B Lode Horizon/Lode Horizon), but the thickness of these sediments is greatest near mineralisation. At orebody scale, the events that deposited the base metals occurred when little or no manganiferous material was being deposited. This suggests pulses of mineralisation or some localised, active agent ( $fO_2$ /biological?) caused the preferential deposition of Pb-Zn-Ag sulphides.

The reasons for the huge accumulation of lead-zinc sulphides, manganese, calcium carbonate, fluorite and apatite at BH are still not clear but are probably indirectly related to volcanic activity.

In summary, the following features characterise the depositional environment of the BH deposit;

- There is a spatial and geometric association between the Lode Sequence and a bimodal volcano-sedimentary complex, but the formation of deposit is probably only indirectly associated with volcanic activity,
- The deposit formed in the position where the volcanic complex lenses out into the surrounding sediments. The environment of ore deposition is associated with the position where potosi type gneiss units diminish to thin amphibolite and calc-silicate horizons.
- The Lode Sequence formed as a suite of chemical, clastic and chemically enriched clastic sediments,
- The orebodies and Lode Sequence were formed on the sea floor in a relatively high-energy sedimentary depositional environment.
- The Lode Sequence probably formed as an elongate mound.

## 7.5. EXPLORATION FOR BROKEN HILL TYPE SYSTEMS.

### 7.5.1. Exploration Models based on Stratigraphic Associations.

Stratigraphic models have been used successfully since the earliest days of exploration for BHT deposits. Even the earliest prospectors on the BH field recognised the lithological associations of Charles Rasp's original find, sought the same rock types and explored them; often with some success. In the last 60 years of exploration at BH, stratigraphic concepts were used during the exploration, resource definition, development and mining of the orebodies within, or associated with the Garnet Quartzite Horizon (e.g. MacKenzie and Davies, 1990) and were the framework upon which the successful discovery of the Potosi Orebody was based (Larsen, 1994). The understanding of the stratigraphic succession of the Mine Sequence, which guided the definition drilling of the Potosi Orebody, also guided the further definition drilling of the nearby Silver Peak Extended zones. In the 1970's this same concept had resulted in the drilling campaign that discovered the Silver Peak zone, led to the sinking of an exploratory shaft, and the extraction of a large test sample of lead-rich ore. Stratigraphic associations have guided all of exploration success within the BH mine leases since its BHT potential was first recognised in the 19<sup>th</sup> Century. The lithological association model that has been so successful at BH has also been used to identify other potential BHT host terranes in Australia, including that which brought about the recent discovery of the Cannington deposit in the Mt Isa Block (Skrzeczynski, 1993; Walters 1996a). Stratigraphic models of BHT style mineralisation are very robust.

As King and O'Driscoll (1953) suggested, and Larsen (1994) has confirmed, stratigraphic concepts and the identification of lode rock associations are still the keys to the discovery of BH type orebodies in the Willyama Supergroup. Therefore, the key to future exploration for BH type orebodies in the BH region lies in the stratigraphic framework of Pasminco Limited and the Geological Survey of New South Wales and in the application of geophysical techniques to the interpretation of sub-surface areas by the extrapolation of the well-understood outcrop stratigraphy into these areas. In the outcrop area, only persistent drilling and perseverance will result in success (e.g. Larsen, 1994).

The relationship between BH mineralisation and calcium carbonate, or calcium-bearing silicate rich rocks is considered one that could be important in exploration programmes for orebodies of this type. Calcium-rich rocks are rare in the Willyama Supergroup and such rocks located in the correct position (see below) may be a means of focussing exploration.

### **7.5.2. Target Horizon.**

The main BH orebodies lie within the transition zone between the Thackaringa and Broken Hill Groups. In the mining field area, the footwall of 3L lies within tens of metres of the Footwall Quartzofeldspathic Gneiss, a unit that is interpreted to be a part of the Thackaringa Group by the Geological Survey of NSW (e.g. Willis et al., 1983). Most other BHT occurrences in the Willyama Supergroup also occur in this zone. The stratigraphic interval representing the base of the Broken Hill Group and the upper part of the Thackaringa Group is the key target horizon for explorers within the Willyama Supergroup.

### **7.5.3. Margins of Volcano-sedimentary Complexes.**

The main BH mineralised system is located on the northwestern flank of a volcano-sedimentary complex that is represented by the Footwall Quartzofeldspathic Gneiss, Consols Amphibolites and the ABM Potosi Type Quartzofeldspathic Gneiss. The deposit is located at the thinner, southwestern end of the complex and lies at the position where the metavolcanic rocks lens out into clastic metasediments. The long axis of the mineralised system parallels that of the complex (Figure 7.9). Is this position of genetic significance? Could economically significant mineralisation occur in similar positions adjacent to the thinned margins of other such lenticular, elongate complexes in the district?

Thickened sequences of acid meta-volcanics and amphibolites, which represent volcanic complexes, may possibly be indicators of the presence of large BHT systems. Deposits may be located on the thinner margins of thick Potosi type gneiss units or sequences, where they merge into amphibolite horizons. Low-grade BHT occurrences that are associated with the tapering margins of large volcano-sedimentary complexes

(Potosi type gneiss, quartzofeldspathic gneiss and amphibolite complexes) may be particularly worthy of re-examination.

Within the MinSeq, a spatial relationship is observed between the terminations of the linear lenses of Potosi type gneiss units and occurrences of significant mineralisation. Potosi type gneiss units are lenticular in section but have a high aspect ratio, being elongate on a regional scale. Mineralised occurrences are also elongate and are approximately parallel to the lateral terminations of linear lenses of Potosi type gneiss in the ABM Potosi Type Quartzofeldspathic Gneiss and in the Upper Potosi Type Quartzofeldspathic Gneiss in the Mine Sequence. The plunge of the long axes of Potosi type gneiss lenses is approximately parallel to the linear mineralised zones (including the main orebodies) within the Mine Sequence. It is possible that significant occurrences of mineralisation occur at positions where Potosi type gneiss terminates. Mackenzie and Gow (1970) proposed an inverse relationship between Potosi type gneiss and mineralised occurrences.

A simplistic exploration concept is suggested as worthy of further testing. Map out the geometry of large bodies of Potosi type gneiss. Define the flanks (terminations) and then model in 3D (or in stacked level plans) and examine if there is a correlation between linear mineralised bodies and these regions.

#### **7.5.4. High Aspect ratio of the BH Mineralised System.**

The extreme linearity and high aspect ratio of the BH mineralised system is a primary feature. If the distal end of a large and steeply plunging BHT system was to intersect the surface in a structurally complex terrane, such as the Willyama Supergroup, it may appear as only a very weakly mineralised package of lode rocks and seem of little significance. Widely spaced drilling may have missed the main mineralised cores of long and thin zones, if the drilling programmes were designed to intersect broad flat sheets of mineralisation. Many of the known small BHT deposits in the Willyama Supergroup may actually be the distal ends of larger linear systems.

Careful geological compilations of known BHT occurrences in the BH area should be undertaken, and used to guide carefully targetted drilling programmes that are designed to test for linear and pipe-like mineralisation. Tightly focussed drilling that is

targetted to chase narrow 'shoots' down-plunge could bring results, especially if coupled with downhole geophysics.

Re-evaluation of known BHT occurrences should be undertaken in the light of this model.

#### **7.5.5. The 4.5 Horizon.**

The discovery of the economically mineable Potosi orebody within the 4.5 Horizon by Pasminco Mining (Larsen, 1994; Morland & Leever, 1998), confirmed the economic potential of this part of the Mine Sequence. At least one other significant zone of mineralisation has been defined within this unit in the Pasminco Mine (Haydon & McConachy, 1987), but has not as yet yielded an economically mineable resource.

Apparently isolated intersections of high and low-grade sulphides have been made within this horizon and the Potosi Orebody has revealed its potential. A focussed reassessment of the zone, based on the structural and stratigraphic reassessment of the BH mining field presented here is warranted.

#### **7.5.6. The Fitzpatrick Zinc Lode.**

A cursory examination of the geological relationships between the main orebodies and the "Fitzpatrick Zinc Lode" (FZL) (e.g. Aitcheson, 1993) was made during this study. On the 36 Level of North Mine, it is probable that the FZL mineralisation is not in a separate and overlying Zinc Lode Horizon, but is an extension of 2L or 3L that has been transposed or dislocated from the main orebodies. Several structurally dislocated, but economically significant, ore grade zones were discovered in the upper levels of North Mine by early mine geologists, in similar positions relative to the main orebodies (e.g. Garretty, 1943), and were shown to be continuations of 2L.

Alternatively, the FZL could be a mineralised zone within the 4.5 Horizon. There is considerable potential for the geological reinterpretation of this economically significant zone. A more complete understanding of the North Mine "Zinc Lode" may generate economically significant ore zones, whether they be 4.5 Horizon or dislocated 2L or 3L.



### 7.5.7. Other Models.

There have been various new, partly new, or reinvigorated 'old' models, for the genesis of the BH deposit put forward by several workers in recent years. Structural models such as that of White et al (1995) and Rothery (2001), metasomatic models such as that of Williams, et al., (1996) and metamorphogenic models such as that of Ehlers et al., (1996) are not supported by the abundant evidence preserved by the orebodies, which shows that the mineralised horizons and companion rocks were in place prior to pegmatite formation and the earliest phases of deformation. Such models do not provide any new exploration criteria that could be used in the search for a BH type orebody because they provide no new criteria by which an area of interest could be refined, and then targetted for more detailed exploration. Not only are such models negated by a lack of evidence preserved in the rocks of the mining field, they also cannot be applied in the field.

Variants of such models that argue for a profound syn-tectonic and syn-metamorphic redistribution of the constituents of the orebodies are also invalidated by the present structure and stratigraphy of the orebodies, Lode Sequence and Mine Sequence. There is no large-scale structural control on the distribution of mineralisation. F2 folds cross the ore horizons and Lode Sequence Stratigraphy. Yet, some of the recent models do suggest some interesting processes and mechanisms of sulphide mobilisation (and the mobilisation of other constituents of the orebodies, such as quartz) that the field evidence suggests did take place in the deposit, at small scales, during deformation and metamorphism. Future research into BHT systems will be more fruitfully focussed if it uses the results of this study as a context for further investigation.

### 7.5.8. Final Statement on Exploration Models.

During this study, no compelling arguments against a syngenetic origin for the BH orebodies have been identified. As a result of the recent work, it is concluded that since the work of King and O'Driscoll (1953) the BH deposit has been well enough understood, from an exploration geologist's point of view, to bring about the discovery of its successor in the district. The stratigraphic control on the BH orebodies recognised by King and O'Driscoll (1953) and the subsequent 51 years of exploration based on those concepts should have brought about the discovery of the next world-

class orebody within the Willyama Supergroup. As this has not happened in the outcrop area, it can only be concluded that it is not there, or at least not within the detection limits of current technology. However, smaller (less than ten million tonne) orebodies such as the Potosi Orebody remain a realistic target in the outcrop areas of the Willyama Supergroup.

This study has shown that stratigraphic controls and associations are still the most relevant guides to the search for BHT systems because the controls on, and indicators of the BH deposit are mostly early (S0) stratigraphic features, as have been traditionally used by explorers in the Willyama Supergroup. The most important stratigraphic indicators of mineralised horizons in the BH area are packages of distinctive 'lode rocks' including blue quartz-rich, manganese-garnet bearing rocks. It is suggested that such rocks, seen in association with calcic lithologies that include calc-silicate horizons, amphibolite and quartzofeldspathic (plagioclase-bearing) gneisses may be of the most interest (Webster, 1996a).

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# APPENDICES

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## Catalogue of Appendices

**Appendix 1.**                      On CD, in pocket at rear of thesis. Digital geological maps in pdf format of all of the major underground mine levels of the Broken Hill mining field.

### **Appendix 2 (Chapter 1)    HISTORY OF THE BROKEN HILL MINES**

- A2.1.            CLIMATE & RAINFALL
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- A2.3.            DISCOVERY OF THE BROKEN HILL DEPOSIT.
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- A2.6.            MINING AT BROKEN HILL.
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- A2.7.            MINING DEVELOPMENT AND EARLY GEOLOGICAL WORK AT BROKEN HILL
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### **Appendix 4 (Chapter 3).    UNIT DESCRIPTIONS OF THE WILLYAMA SUPERGROUP**

## **Appendix 5 (Chapter 4) DRILL HOLE LOGS – MINE SEQUENCE**

- Appendix 5.1. Log of DDH 7026. Pasminco Mine, southern lower 2 Lens.
- Appendix 5.2. Drill hole log of DDH 7490, Pasminco southern leases, cross section 292.
- Appendix 5.3. Drill hole log of DDH 3355, Pasminco northern leases, Silver Peak prospect. (See cross section 31.00; Figure 4.42).
- Appendix 5.4. Typical intersections of the Hangingwall Quartzofeldspathic Gneiss, Pasminco southern leases, section 340.
  - Appendix 5.4A. DDH 7784.*
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- A6.2. MAPPING OF LITHOLOGIES.
  - A6.2.1. Mapping of Marker Units.
- A6.3. FORM SURFACE MAPPING AND FORM SURFACE EXTRAPOLATION
  - A6.3.1. Fold geometry.
  - A6.3.2. High-grade Shears
- A6.4. FEATURES WITHIN THE OREBODIES THAT RELATE TO DEFORMATION.
  - A6.4.1. Timing of deformational and metamorphic events in orebodies

## **Appendix 7 (Chapter 6). LEASE GEOMETRY CONTROLS THE STREET LAYOUT OF THE CITY.**



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## APPENDIX 1

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Geological maps of the Broken Hill mining field. Contained on CD in rear pocket of thesis.

A catalogue of the maps in Excel format is also contained in the CD.

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## APPENDIX 2. HISTORY OF THE BROKEN HILL MINES

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### A2.1. CLIMATE & RAINFALL

The Broken Hill region lies in the arid far west of New South Wales. It has an average rainfall of 235 mm. Summers are warm (January average day temperature 32°C) and winters mild (July average day temperature 15°C).

### A2.2. EARLY HISTORY OF THE BROKEN HILL DISTRICT

Prior to the early pastoral settlements and the later discovery of silver and lead mineralization, the region was sparsely populated by Aboriginals. Evidence for an Aboriginal presence in the region is widespread and of great antiquity however, and includes such sites as Mootwingee National Park (130 kilometres northeast of the city); 44,000 year old rock engravings in the Olary region of South Australia (Flood, 1990); the Willandra Lakes region to the southeast and the Sturt Meadows site, 80 kilometres to the north.

Occasional stone flake scatters and isolated artefacts composed of white quartz and silcrete (imported to the district) are seen in the area of the city, especially in the creek systems. Such sites attest to the presence of Aboriginal people in the Broken Hill area prior to European settlement (Nicholson 1995). A very significant site of Aboriginal occupation occurs approximately 15 kilometres to the north of Broken Hill, within the valley of Stephens Creek (Mason 1990, quoted in Nicholson, 1995). Historical records refer to the presence of many huts in this area (Brock 1988, quoted in Nicholson, 1995).

Captain Charles Sturt was the first European to traverse the Broken Hill region in 1844 and is said to have sampled the lode outcrop (samples that were later lost and never assayed). Pastoralists entered the district from 1855 onwards but the carrying capacity of the land was very low. Scattered sheep stations were the only European settlements in the district until well sinkers at Thackaringa discovered silver in 1875. This event heralded the beginning of a series of small mines in the district. By 1882 the settlement of Silverton had grown into a sizeable town to service the small silver mines in the

Thackaringa area (of which the Umberumberka mine was the most notable). At the time of the discovery of the Broken Hill orebody, Silverton was the largest settlement in the district. Miners there had failed to recognise the mineral potential of the "broken hill", referring to it as the "hill of mullock" (Solomon, 1988).

### A2.3. DISCOVERY OF THE BROKEN HILL DEPOSIT.

The Broken Hill orebody outcropped near the western boundary of the 900,000-acre Mt Gipps Sheep Station, some 25 kilometres southeast of Silverton (Blainey 1968). In 1883, the outcrop was a conspicuous, ragged, saw-toothed, gossanous hill, which comprised the highest part of a narrow, northeast-southwest trending ridge that was several kilometres long. The strongly asymmetric ridge sloped gently to the northwest, possessed a strongly bluffed summit and a steeper southeastern side. It was composed of "ferruginous quartzite, quartz 'greisen', feldspar, porous brown iron ore or gossan and oxide of manganese (pyrolusite) with patches and veins of crystallised carbonate of lead" (Wilkinson, 1884). There were sharp undulations at the crest formed by a manganiferous and ironstone cap which stood boldly out from the surrounding metasediments, to a height of 15 or 18 metres (Blainey, 1968). Large blocks of iron and quartz had fallen from the capping and rolled down to the base of the hill on the southeastern side (Warren, 1903). Manganiferous oxide was traceable for about a "mile and a half" along the low ridge. It varied from 20 to 100 feet thick, though the exact width was difficult to determine because of the accumulation of eroded debris on either side (Jaquet, 1894). As Blainey (1968) states, "*of all the lodes discovered in Australia in the 19th Century, Broken Hill probably had the most conspicuous outcrop*".

Silver-lead ore was first recognised in the Barrier Ranges in 1876 when two well sinkers discovered silver rich ore in a well they were putting down near John Stokie's pub at Thackaringa (Blainey 1968). Further small but rich silver discoveries followed, but it wasn't until the Umberumberka silver lode was discovered in 1882 that Silverton, the main settlement of the region, developed. Prospectors from Silverton had examined the gossanous outcrop on the "broken hill" and considered it worthless. However Charles Rasp, a boundary rider based at the 'Nine Mile' outstation of the Mt Gipps Station, some 6.5 miles to the north of the hill, considered that it must have some mineral potential. He collected samples of the dark material for assay, in the belief it may be tin oxide. Upon analysis the samples were found to contain traces of silver and lead. In September 1883, with the help of two well sinkers, Rasp pegged the

darkest part of the outcrop (still in the belief that it may contain tin oxide). It is Rasp's pegging of the first leases at Broken Hill that is now taken as the official date of his discovery of the deposit. On the advice of the station manager, Rasp sought extra capital to expand the lease holdings over the hill and so the 'Syndicate of Seven' was formed (the station manager, bookkeeper, sheep overseer, station hand, the two well sinkers and Rasp).

They sunk a shaft, which eventually intersected the rich secondary silver zone. The highly depleted region that they initially passed through almost caused the syndicate to go broke. They persevered following a report from a Victorian geologist who recognised the potential of the deposit (Taylor, 1884, reported in Solomon, 1988).

In 1885, following the appointment of the first manager, the Broken Hill Proprietary Company Limited (BHP Ltd) was floated to develop the deposit. The board consisted of the remaining members of the original syndicate and newer speculators who had replaced some earlier shareholders who had lost faith in the venture and sold out. The board promoted the deposit themselves with very little hard data, depending more on their enthusiasm and faith in the deposit to generate development capital.

Forty-acre leases were pegged to the northeast and southwest of the "broken hill" soon after Rasp registered his claim and these leases were eventually consolidated into major companies. The leases at the northeastern end of the field became North Broken Hill Ltd (now known as North Ltd), while those at the southwestern end of the field became Broken Hill South Ltd, Zinc Corporation and New Broken Hill Consolidated Company Limited. The latter mines became the main operation of Pasminco Limited in 1988.

#### **A2.4. HISTORY OF BROKEN HILL CITY.**

The City of Broken Hill is located at latitude 31°57'S and longitude 141°28'E. It is 304m above sea level. The city developed on the flat plain to the immediate west and northwest of the "broken hill" and was originally one of a number of small such townships that were established in the early 1880's to service the many small mines and prospects then being found in the district.

There were once several small townships in the district around Broken Hill. One of these was officially known as 'Taltingan', but was always known by its residents as "Round Hill" because, like Broken Hill (whose official government name was "Willyama") its government name was never adopted by the locals (Solomon, 1988). Round Hill was established to service the Round Hill mine and other prospects in the immediate area but, like all other small towns in the district, died off rapidly once Broken Hill became established as the premier mining field of the district (e.g. Jaquet, 1894).

The original population of Broken Hill was largely formed by Cornish miners from the long established South Australian copper mining districts of Burra and Moonta. These mining fields were then in a state of decline and the promise of the newly discovered Broken Hill field offered greater long-term employment prospects. By 1891 Broken Hill had a population of 20,000 people and at its peak (1915), reached a population of over 34,000 people (Solomon, 1988). The current population remains static at around 23,000 people.

The City of Broken Hill is the largest regional centre between Whyalla (South Australia) and Dubbo (New South Wales). It is still largely dependant on the lead-zinc-silver orebody (known as the 'Line of Lode') though tourism is rapidly growing in importance. The City's mining heritage is seen as a major tourist attraction and a source of pride to local people.

A detailed history of the development of the City of Broken Hill is beyond the scope of this thesis and the reader is referred to the work of Solomon (1988) and Kennedy (1978). Further reading on the history of Broken Hill includes Blainey (1968; 1989), Carroll (1986) and Kearns (1996a; 1996b).

## **A2.5. ACCESS**

The modern city of Broken Hill is connected Melbourne (849 kilometres), Adelaide (508 kilometres) and Sydney (1,165 kilometres) by sealed highways and regular air services. Passenger trains run to Adelaide, Sydney and Melbourne.

## **A2.6. MINING AT BROKEN HILL.**

Many mines have operated on the Broken Hill Line of Lode during its long history of exploitation. Throughout this thesis, it will be necessary to discuss the geology of various parts of the deposit and the historic mine names and former lease boundaries provide a convenient shorthand method of referring to such regions. For this reason, this section will give a brief history of the mines that have operated at Broken Hill and define the former leases that they occupied. Firstly, the initial discovery of the deposit is briefly outlined. Then a brief history of each mine is presented, with the discussion ordered from southwest to northeast.

### **A2.6.1. The Zinc Corporation and New Broken Hill Consolidated Mines.**

The Zinc Corporation Limited was formed in 1905 to recover zinc from the large volume of residues that could not be economically treated by earlier mining operations. In 1911 some mining leases, then known as the Southern Blocks, were acquired and the company undertook limited mining. In 1936, lease exploration confirmed that large amounts of ore lay at depth and the company undertook a reconstruction of the mine. A flotation circuit was installed in the concentrator and the mine rapidly became the largest producer of the field. The first ore was hoisted up the new "Freeman" Shaft in 1939.

The New Broken Hill Consolidated Company Limited (NBHC) was formed to undertake exploration of the southern extensions of the orebody beyond ZC. Throughout the 1930's and 40's, exploration of the orebody to the southwest continued, with some production areas accessed from the ZC workings. Following the war, the NBHC Haulage shaft was sunk to access these new reserves, followed in 1950 by the NBHC Service Shaft. The first ore was produced in 1944.

All NBHC ore was treated at the ZC concentrator until 1952 when the NBHC concentrator was commissioned. In August 1986 the ZC and NBHC mines were combined into one operation and renamed ZC Mines. In July 1988 ZC Mines and the North Mine (North Broken Hill Ltd) were combined as assets of the Pacific Mining and Smelting Company Limited (Pasmaico Ltd), a new mining and smelting group.



The Pasminco Broken Hill Mine, operating the former ZC-NBHC leases at the southwestern end of the field, is the only remaining underground operation at present and incorporates the former ZC and NBHC leases at the south end of the field. The leases have produced 82.2 million tonnes of ore at a combined lead plus zinc grade of 20 percent since mining began in 1912 (Smith and Spreadborough, 1993) with a total production of 2.2 million tonnes of ore for the year ended June 1993. Recent press releases by Pasminco have stated that the mine will close in the year 2005 if no significant discoveries are made.

#### **A2.6.2. Broken Hill South Ltd (the 'South Mine', ML's 6, 7, 8 & 9).**

The original company acquired ML's 5, 6, 7 and 8 from Messrs. W G and C Maiden and G White in 1885. Active development of ML's 7 and 8 commenced in 1885, at the northern end of the property. Development was chiefly in the oxidised zone until 1890 and until 1893, the company operated a lead smelter. Following a period of uncertainty, resulting from the depletion of the oxidised reserves and the inability to adequately treat sulphide ores, the company rallied when a successful gravity separation process was installed. The centre of operations gradually migrated southwest, following the pitch of the orebodies.

In 1940, Broken Hill South Ltd acquired ML's 9, 10, 11, 12 and 13 surrendered by the Sulphide Corporation Ltd (the Central Mine) and the BHP Co Ltd (Black, 1953)

Until recently, the South Mine leases were held by Poseidon Ltd, through their subsidiary Minerals Mining and Metallurgy Ltd (MMM). The leases have been purchased by Consolidated Broken Hill Limited who intend to re-establish underground mining.

#### **A2.6.3. The Sulphide Corporation Ltd (the 'Central Mine', ML 9).**

The Central Mine developed on the irregularly shaped ML 9, pegged in 1884. This lease was taken out to cover a portion of the original hill that was not covered by the first leases of 1883 (Drew 1997). The irregular shape of ML 9 resulted from an oversight of the original syndicate who are said to have deviated during the pegging of ML 10, because of the dense mulga scrub that once covered this part of the hill (Bridges, 1920).

The company operated until the rich oxidised silver ore was depleted in 1892. The mine was then acquired by the Sulphide Corporation Ltd in 1895 and operated until it was worked out in 1940. The leases were then transferred to Broken Hill South Ltd, which worked the mine from 1945 until 1961 (Drew 1997). The mine produced 6 million tons of ore (Drew 1997).

#### **A2.6.4. The BHP Block 10 Co Ltd (the 'Block 10 Mine', ML 10).**

Block 10 was one of the original BHP leases but was floated as a separate company in 1888. The company was known as the BHP Block 10 Co Ltd. A concentration mill was constructed in the 1890's but was seriously affected by the mine subsidence's and a new mill had to be erected at a distance from the mining area, on Block 10 hill (now the lookout) (Drew 1997).

The mine produced a total of 2.5 million tons of ore before it closed in 1923, after which it was purchased by BHP. Broken Hill South Ltd worked the mine from 1946 until 1960 (Drew 1997).

#### **A2.6.5. Broken Hill Proprietary Company Ltd (the "Big Mine", ML's 11, 12 & 13).**

The first syndicate originally pegged Seven ML's, but by 1888, only the central leases were retained by BHP (ML's 11, 12 and 13), with the rest having been floated off as separate companies (Drew, 1997), perhaps as a means of diminishing the risk. The BHP Mine occupied the leases where the manganiferous ironstone outcrops occurred, with the largest and most continuous located on ML 12.

The first smelting furnaces were installed in 1886 and a second complex was installed in 1888 (Drew, 1997). Open cutting of the hill commenced in 1891 and in 1894 a concentrator was erected (Drew, 1997). The BHP mine reached its peak between 1900 and 1908 but the rich ore was exhausted by 1908. The company finally closed the mine and left Broken Hill in 1939 after producing 12.3 million tons of ore (Drew, 1997).

**A2.6.6. The Broken Hill Proprietary Block 14 Co Ltd Mine (ML 14, Block 14 mine).**

ML 14 was one of the original BHP leases that was floated as a separate company in 1887 (Drew, 1997). The mine originally began on rich oxidised ores and a smelting plant operated on the mine from 1889 to 1894 (Drew, 1997). The mine closed for a period in the early 1900's due to low metal prices but re-opened again in 1906, selling concentrates to the Zinc Corporation. The mine closed in 1928 after producing 1.6 million tons of ore. The area was reworked by North Broken Hill from 1948 until 1952 (Drew, 1997).

The assets of the Block 14 mine were acquired by the Willyama Mining Co in the 1930's and then passed to the North Broken Hill mine

**A2.6.7. British BHP Co Ltd Mine (ML's 15 and 16, the 'British' Mine).**

The British BHP Co Ltd was formed in 1887 to operate ML's 15 and 16 of the original BHP leases. A smelter was built for the mine in 1891 and operated until 1901, when oxidised ore reserves became depleted. By 1910, most of the accessible ore had been mined and the lease was finally sold to North Broken Hill Ltd in 1923 after producing 2.8 million tons of ore (Drew, 1997). North Broken Hill Ltd worked the mine until 1958 and it was again reworked by open cutting (Blackwoods Open Cut) in the 1980's by MMM (Drew, 1997).

**A2.6.8. The Broken Hill Junction Silver Mining Co Mine (ML 39, the Junction Mine).**

The Junction mine developed on the northeastern end of the outcropping lode after first being pegged in 1894. The Broken Hill Junction Silver Mining Co was formed in 1886 and a smelter was erected at Port Adelaide in South Australia. (Drew, 1997). Low lead prices and treatment problems forced closure between 1901 and 1906. A new operation commenced in the latter year based on Browne Shaft and the mine continued until 1923 when it was sold to the Sulphide Corporation. It was purchased by North Broken Hill Ltd in 1929 and was reworked from 1946 until 1962. It was acquired by South Broken Hill Ltd in 1962 and operated until 1972 (Drew, 1997).

In 1963, a haulage drive was put in from the South Mine to Browne Shaft at the 1480' Level. Extensive underground exploration drilling and ore haulage to the South Mine was undertaken on in this drive (Hughson, 1968).

#### **A2.6.9. North Broken Hill Silver Mining Co Ltd (North Mine).**

The Cosmopolitan Mine began operations on Block 17 at the north end of the field in 1883. The mine was sold to a Melbourne syndicate in 1885 to become Broken Hill North Silver Mining Company Limited which was known as the North Mine from that time on (Pasminco unpublished report). A concentrator was erected in 1888 to treat the oxidised ores but these were depleted by 1894. Production from sulphide ores commenced in 1897 (Drew, 1997).

The company became North Broken Hill Ltd in 1912, by which time it had become one of the largest mines on the field. The neighbouring British, Junction, Junction North and Block 14 mines were acquired between 1923 and 1942. No 1 Shaft was begun in 1905 and used for all ore haulage until No 2 Shaft commenced operations in 1933. A new concentrator was built in 1939 adjacent to No 2 Shaft. No 3 Shaft at the northeastern end of the orebody commenced in 1948 and was commissioned in 1962 (Drew, 1997). Towards the end of 1991 the North Concentrator closed, all ore being treated at the NBHC Mill (Pasminco unpublished report, 1995).

Open cut operations took place at No 1 Shaft in 1985. Until the mine closed in 1993, it produced 34 million tons of ore. (Drew, 1997).

Mining at the North Broken Hill Ltd Mine ceased in February 1993, leaving some 0.9 million tonnes in the ground.

#### **A.2.7. MINING DEVELOPMENT AND EARLY GEOLOGICAL WORK AT BROKEN HILL**

A level of understanding of the geology of the Broken Hill orebodies has played a part in mine development and exploration from the very earliest days. The first mine leases pegged on the hill in 1883 followed the conspicuous outcrop and show that Charles Rasp, the discoverer, was the first to recognise a geological feature of the deposit; its strike (Figure 6.1). The heavy black samples collected by Charles Rasp in

1883 were assayed but contained only minor silver and lead (Blainey, 1968). However, he was sufficiently encouraged to persist with testing his discovery.

Once Charles Rasp had pegged the prominent outcrop and a mining syndicate had been formed, scientific attention was focussed on the prospect. It was slow to start however and Wilkinson (1884), the first observer, found that the gossanous outcrop making up the 'broken hill' was composed of ferruginous rocks containing quartz, feldspar, iron oxides or gossan and manganese oxides with "patches and veins of crystallised carbonate of lead". He recognised that the outcrop represented a huge argentiferous lead lode that dipped with the strata, with spurs coming off the northwest side. Taylor (1884, in Solomon 1988) reported to the first mining syndicate that they were developing "*the most extraordinary and largest lode I have ever seen on the Barrier Ranges silver field, or, in fact anywhere*". The earliest geological reports (e.g. Wilkinson, 1884; Taylor, 1884; Wilkinson, 1889) were sought by early companies so that the production permanency and future ore production potential of the field could be determined and investment decisions made. Essentially, geological advice was needed to determine whether the development of Broken Hill lodes was worth persevering with.

In 1886, William Corbould, a contract assayer in the embryonic Broken Hill settlement, was sidetracked from completing the first geological map of the Broken Hill mining field when the local Police Constable took umbrage at a practical joke that Corbould had played on him. It is not recorded if Bill Corbould ever completed the map, or what became of it (Hore-Lacy, 1981). The first published geological map was produced by C. W. Marsh in 1888 and published in

Most of the early geoscientific interest in Broken Hill drew from the mining sources, or those of local interested individuals and could thereby propound theories about its geological origins. Interest in the structure of the lode may also have stemmed (in the early days) from the owners of the leases at the northeast and southwestern peripheries of the field wishing to know if the orebodies would extend into their leases; or whether there would be a remake, parallel orebody or other such remake in their leases or nearby. Rapidly, once the field was established, early geological reports on Broken Hill focus on two areas; the mineralogy of the lode and the structure of the lode.

Within ten years of its discovery, underground development and mining had revealed that there were ore horizons rather than a “fissure lode”; that the ore horizons were highly convoluted, but best developed in antiformal fold hinges; that there were two main orebodies, and that the deposit plunged northeast and southwest (e.g. Pittman, 1892). Also, within that first ten years, the metallurgical requirements of the smelters and concentration works had revealed the gross mineralogical variations in the orebodies; particularly the oxidised zone. So the data that was collected to improve the efficiency of mining and smelting outlined the essential characteristics and main geological features of the Broken Hill lead-zinc-silver deposit. Then the geoscientists arrived.

One of the earliest published accounts of the underground geology of the mines (Jamieson and Howell, 1893) was derived from such sources and provided a classification of the underground ore types then categorised by their smelting characteristics. The first comprehensive geological investigation of the geology of the Broken Hill mining field (Jaquet, 1894) also drew heavily from such mining and metallurgical sources when dealing with the underground geology of the mines. Marsh (1893) presented a geological map of the surface geology of the BHP, Central and Block 14 mines and remains the only known published source of information about many of the details of the geology of the surface geology on these mines.

Geological investigations were also undertaken to determine the causes of a number of serious mine “creeps” (subsidence's in the workings) and to determine if the mine management was culpable. Such studies were the first geotechnical work at Broken Hill.

#### **A2.7.1. Mineralogical Investigations.**

In addition to the increasing understanding of the orebody geometries that developed in the 1890's, there was a parallel field of scientific investigation driven largely by amateurs. This was the collection and identification of the minerals of the oxidised zone. Much of the published work consists of mineral descriptions and analyses carried out on material collected by miners and sold or traded to collectors. One of the most significant collections was that of the publican Charles Aldridge, of the “Duke of Cornwall Hotel”, who traded specimens for beer. The small fragments of the oxidised zone collected by Aldridge in this early period, and by others like him, preserve a



record of the shallow parts of the BH orebodies. There were also some descriptions of oxidised mineral localities, such as the vughs described by Baye (1895), and of the broader geological features of the oxidised zone (eg. Jaquet, 1894; Clark and Howell, 1893) published in this period.

The oxidised zone of the Broken Hill deposit produced a rich variety of minerals. Jamieson and Howell (1893) were the first to identify and map the mineralogical zones within the oxidised portion of the orebodies. The different mineral complements of the oxidised and partially oxidised ores required different treatment and smelting processes and so were defined on that basis. Jaquet (1894), using BHP mining data, defined a series of mineralogical zones in the oxidised part of the deposit. Plimer (1984) also identified zones within the secondary alteration of the orebodies. Birch and van der Heyden (1997) identified mineralogical zones in the Block 14 and Kintore open cut.

#### **A2.7.2. 1890's to 1910.**

By the early 1890's, the mines had penetrated to relatively deep levels and it was realised that the oxidised ores were giving away to sulphide ores. Marsh (1893) reported that within the silver and lead-rich oxidised zone there were many "irregular masses of zinciferous galena" encountered, the centres of which retained primary zone mineralogy. Such masses were interpreted to be zones of incomplete alteration of the primary sulphides. At the time, lead and silver, extracted in the form of galena, was the most valuable mineral of the primary sulphide zone at Broken Hill and the zinc sulphide sphalerite, intimately inter-grown with the galena and was virtually valueless. The metallurgical processes of the time did not allow the two intimately intergrown minerals to be economically separated and this became a rapid focus of metallurgical research on the mines and at the smelters for the next decade. The research into an economical technique to separate the galena from the valueless zinc sulphide became the major focus of Broken Hill research for the next 10 to 15 years.

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## APPENDIX 3. MAP COMPILATION METHODS.

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### A3.1. INTRODUCTION.

During this project, an emphasis has been placed on the use of existing geological backs mapping of sills and stoping contours of all major levels of the mines, with a control provided by the extensive mapping by the author in the Pasminco Mine. Geological plans have been compiled for all sill levels of the current and former underground mines at Broken Hill. In most major mines, underground levels were developed at 100 feet (30.48 metres) or 150 feet (45.78 metres) intervals.

Mapping compilations, and the interpretative geological level plans based upon them, allow folds, shears, faults, alteration zones, lode rock units and lode pegmatite units, and orebody geometries, to be defined, and traced from surface to depth, level by level in regularly spaced intervals. In this way the changes that take place in fold style, shear width and orientation and their influences on the geometry of the mineralisation can be examined.

The level of geological detail is much greater in underground backs mapping compilations than in drill hole based cross sections. Level plans offer a detailed, outcrop-based method of geological interpretation in comparison with traditional, drill hole-based cross sections, which are based on pinprick data points that are often off section.

Most structural interpretations of the BH deposit have generally focussed on drill cross sections. Such sections are constructed largely from drill hole information and not from observed geology. Level plans on the other hand are constructed from actual mapping and give a more accurate and true picture of the geology. They also have the advantage of documenting form surface information and details of the geometry and internal gangue variations within the orebodies (not to mention strike and dip of banding and fold plunges, whether directly or in an interpretable fashion). The most detailed geological information on the BH deposit has always been gathered in plan and yet it has rarely, if ever, been utilised to interpret the geology of the deposit. It has

usually been compiled into sections, which are then used to interpret structure and stratigraphy. No other information exists that can be used to so directly relate orebody geometry to wall rock structure. Geological cross sections and the interpreted stratigraphy they present are all interpretative.

Previous workers have utilised interpretative cross sections to determine the structure of the central region of the deposit (e.g. Gustafson, 1939, Gustafson et al., 1950; King and O'Driscoll, 1953). Sections such as this are compiled from drill hole information and underground development/mining openings and are adequate for determining orebody geometries, however they generally lack any other detail. The plan-based approach adopted here (see below) has revealed details about the structure that interpretative sections do not show.

Section-based interpretations result in overly simplistic models. Use of cross sections has not been abandoned totally however, and several detailed shaft sections of key areas, compiled from wall mapping of successive levels have been incorporated into this reinterpretation. Serial sections of the area, reinterpreted from the work of Gustafson (1939) have also been utilised to show the changing geometry of fold structures throughout the mines area.

### **A3.2. PURPOSE OF THE MAP COMPILATION.**

The geological level plan maps were compiled to achieve the following;

Lithological correlation of,

1. companion lithologies (lode rocks),
2. orebodies,
3. gangue zones, and
4. lead grade zones

For the identification of form surface trends within metasediments and lode rocks so that,

1. folds styles and axial trace trends within the orebodies can be defined and their orientations accurately plotted,
2. shears in high grade gneisses could be accurately defined, and so that
3. faults and later folds could be defined

### A3.3. LIMITATIONS OF THE MAPPING COMPILATION.

During the compilation of some mine level map sheets, transferring information between mine grids, primary sources with a variety of original scales has affected the precision of the compilations. Accuracy of scale and grids may vary by anything up to 20 metres. This level of accuracy is perfectly adequate for a structural study such as this one but the information would require further work before it could be used in the following ways;

1. Wire frame models (though the polygons here could be quickly and easily converted to .dxf or similar files for importation into a wire frame modelling programmes) – such a model will be much more accurate than one derived from more generalised cross sectional interpretations.
2. 3D ore resource modelling
3. ore resource calculations

#### A3.3.1. Omissions in the geological data set.

##### *1. Near ore stratigraphy and structure*

Key areas of the near-ore stratigraphy have been observed in underground exposures where accessible. However, to compile a reasonably comprehensive view of the near-ore stratigraphy, underground mapping has been used in conjunction with densely drilled areas, particularly those on the Pasminco Mine, where the author has logged many hundreds of metres of core (especially in the NBHC “Lead Lode Southern Panel”). Such limited areas provide information about the host sequence stratigraphy that can be extrapolated to less well-defined areas of the mining field.

##### *2. Relationship to regional structure and stratigraphy models.*

Throughout this project, the focus has been on the mining field, which extends from the Southern Cross area of the Pasminco Mine, to the Fitzpatrick region of North Mine (including the Western Mineralisation). The 2K Mineralisation, 4.5 Horizon (including the Potosi Orebody), the southern extensions and the northern leases mineralisation (and all of the satellite mineralised zones that they contain) do not form a major part of

this project and are only discussed briefly. The boundaries of the study area are approximately those of the former ML's of the original mining field (Figure 1.1)..

The sequence of structural events used in this thesis is not directly applicable to the surrounding region and is based on that of Webster (1994a; 1996a).

### **A3.4. GEOLOGICAL MAPPING.**

#### **A3.4.1. The Nature of Mine Geological Mapping.**

Mining geology is a specialised branch of the geosciences that uses the techniques of geology to explore, define, describe and assess the economics of exploiting a mineral occurrence. Like all branches of the geosciences, it requires the recording for analysis of observations of the natural world. However mining geology is a field of study in which the sites of these observations are often only seen once and then are no longer available for re-examination. Development drive and stope faces are rapidly mined away and entire mine levels become inaccessible. Mines eventually close, leaving their workings inaccessible. So in mines, key localities rarely remain for others to re-examine and it is often difficult to return to a key locality and re-examine it. As a branch of geoscience, it is more dependant than most on the written or graphic mine records (underground "backs", face and wall mapping, bench face mapping, costean mapping), exploration programme records or drill core or sampling sites. The written or graphic record of observations may be the only source of information on a locality. These localities are, in a sense, only accessible through the eyes of our predecessors.

Geological interpretations in the horizontal plane, using mapping data, reveal much more about the geology of parts of the deposit, such as the Garnet Quartzite Horizon (see Chapter 4), than drill core-based cross-sectional interpretations. Such interpretations provide detailed information on the relationships between the ore lenses and the other important rock types that comprise the Garnet Quartzite Horizon. Detailed, mapping-based interpretations also reveal many details of the relationship between the ore lenses and the regionally significant Lode Horizon.

The sources of geological information are varied and range over the entire period that the deposit has been mined and explored. The available mapping dates from several phases of exploration, government survey, comprehensive company studies and ore

production orientated mine geology recording. Many investigations predate 1939 (Jaquet, 1894; Scientific Society of Broken Hill, 1910; Mawson, 1912; Andrews, 1922; Gustafson, 1939). Of particular importance is the work of the Central Geological Survey, or CGS (Gustafson 1939; Gustafson, et al., 1950).

By far the largest mapping databases are those of the mining companies. The company mapping of greatest extent, consistency and quality dates from after 1948. Mining company mapping was undertaken for a variety of reason, mostly related to ore production. Underground geological mapping is used in mine planning (development layouts, blast hole ring design, stope design), in-mine exploration and ground condition prediction. So company mapping is variable in its purpose for being and in quality.

In the South Mine, geological mapping is not readily accessible; it is restricted to stope wall geology and was focussed on recording the contacts of the mineralisation. South Mine mapping lacks useful detail and was mostly undertaken by Mine Surveyors, rather than mine geologists (Newton, 1968). In the North Mine, mapping within the mineralisation was undertaken for visual grade estimations for production reconciliation's with mill figures and to establish the orebody geometry for mine planning purposes. In the Zinc Corporation (now Pasminco), mapping was undertaken for similar reasons to the North Mine except a greater emphasis was placed on internal orebody gangue variations (often to define areas of low grade mineralisation), some banding orientations and wall rock stratigraphy.

Pre-1939 backs mapping usually records the orebody contacts, the gangue mineralogy of the mineralisation (important in orebody type recognition), foliation trends in wall rocks, dip of foliation, the trace of minor fold structures, plunge of minor folds, brittle fault zones, some retrograde shear zones, dykes and occasionally stratigraphic markers such as amphibolites and Potosi type gneiss units.

Once the vagaries of scale and differing geological legends are overcome, it becomes apparent that the Broken Hill deposit is one of the best recorded of any in Australia.

### A3.4.2 Mapping Practices.

The standard geological mapping practices of Pasminco in Broken Hill have been followed during this project and represent a reasonably standard process that has been used in other Broken Hill mines and elsewhere, both recently and in the past.

Underground mapping at Broken Hill has usually been undertaken by recording the geology as it is exposed in the “backs” or ceiling of horizontal development drives. The backs geology is plotted in such a way that the resulting map appears as if the observer is looking down upon the drive backs. Drive heights have varied from 2 to 6 metres and average 4.5 metres at present. Mapping of drive, winze stope panel and rise walls has also been carried out, though less frequently (e.g. see Webster 1993; 1994a).

In working mines, geological mapping is usually undertaken as soon as possible after firing, because dust and fumes quickly accumulate on drive walls and backs and rapidly conceal the geology. So mapping tends to be done in short strips of less than 50 metres, in working areas of the mine. The impact of mining machinery movements, ground securing, preparations for the next firing, ventilation availability and other production considerations can influence the amount of time that a geologist has to map an area. Also time consuming is the general need to wash down the walls and backs to expose the geology. So usually the time available for geological mapping is not very long. Such realities of working in a production area of a active mine influence the amount of data that it is possible to obtain. Generally, orebody contacts, zones of low-grade mineralisation and faults and shears that may affect ground stability are the three mapping priorities of a mine geologist.

Underground geological mapping usually involves the use of survey plans as base sheets, survey stations as key datum points and a compass and tape measure. In the past, theodolite and chain were used. The mapping process involves locating the nearest survey station for a benchmark and laying a tape measure from that point, parallel to the drive walls and marking 2 metre or 5 metre intervals along the walls in paint or chalk. Information is recorded directly onto a scale plan of the drive or, if the surveyors have not picked the area up, a copy of the design plan for the area. In the latter case, the information can be later traced onto the actual survey outline. Base plans are usually 1:500 scale or 1:250 scale. The geology is then recorded by plotting



the point (measured in metres from the survey station) at which each geological feature (bedding plane, joint, fault, fold axial trace, orebody contact etcetera) enters the walls of the drive. By building up a series of factual points, a geological map is produced. Features in the centre of drives can also be plotted relative to the measured intervals marked on the walls. For sinuous drives, direct measurements are made from the survey station, along a compass bearing to the point where the geological feature enters the wall of the drive.

The direct comparison of modern mapping and earlier generations of geological mapping is possible because there is an overlap in the Pasminco Mine between areas mapped by Andrews (1922), Gustafson (1939) and modern generations of ZC and Pasminco mine geologists. Re-accessing of previously abandoned mining areas has also allowed some modern mapping, including that of the author, to be done in areas that have not been accessed since the 1920's and 1930's. The result is that direct observations can occasionally be made of the structures and features that were mapped by geologists 60 or 70 years ago. A very accurate picture of the types of structures that these early geologists were mapping can be gained and a feeling for the accuracy of their mapping can be developed. In all cases where such a direct comparison has been possible, the standard of former mapping has been very high. So the geological mapping compiled in Andrews (1922) and Gustafson (1939), the two major sources of information for the central region and much of the southern and northern regions of the Line of Lode has been shown to be reliable and accurate and the features they were seeing were identified with confidence. It can therefore be used to interpret the geology of parts of the Line of Lode that are no longer accessible.

### **A3.5. MAP SHEET COMPILATION.**

Existing mapping has been compiled and reinterpreted to produce geological maps that emphasise the orebody and wall rock structure, with a particular focus on form surface trends of banded ore and wall rocks. The technique used is that of Webster (1994a). Maps have been completed for every major underground level in the deposit, with the exception of the 22 to 25 Levels of the Pasminco Mine. Fold and shear structures can now be followed throughout the deposit and their control on the geometry of the orebodies can be seen.

Large scale features of the deposit, such as high grade shears, folds and orebody geometries that may not be apparent while observing limited exposures during short underground visits, or in small strips of mapping, become apparent if all available mapping information is compiled into one view. So the compilation of small segments of mapping, face sketch information and even photographs into geological maps and interpretative geological plans of mine levels is necessary, before a comprehensive picture of the geology of a level can develop.

Structural and stratigraphic compilations were carried out on 1:1500 scale photo-reductions of sill mapping, scanned imperial scale original plans or scanned images and figures from publications reports and presentations. Apart from the initial work, most compilations have been completed in the digital form.

Form lines defined by metasedimentary and structural banding and major stratigraphic units both within and outside the orebodies were plotted and used to interpret the geometry of fold structures, and shear zones (which is a recognised technique for deciphering the structure of complexly deformed, high grade metamorphic terranes (e.g. Passchier et al., 1990). The trace of metasedimentary banding and the banding within mineralisation is the basis of much of the structural interpretation presented here. Form line traces delineate the style and orientation of folding within the mine area. Abrupt re-orientation and/or truncation of the metasedimentary banding within broad planar belts are interpreted as zones of high grade shearing and attenuation. Ore lens geometry also provides information, which is useful in structural interpretation, particularly providing macroscopic movement sense indicators. Gangue minerals and sulphide textures have been used to define the metamorphic grade of each deformation.

#### **A3.5.1. Mine Survey Plans.**

Mine surveyors produce very accurate plans of the location, height, relative level and width of underground drives. Such plans usually represent the drive dimensions at human shoulder (theodolite) height. Surveyors place survey stations at regular intervals along drives (typically every 50 metres) though this has differed in the past and the survey station location is marked on survey plans. Mine survey plans form the base sheets for geological mapping at Broken Hill.

### A3.5.2. Mapping Scales.

In this research project, all mapping has been interpreted at its original scale so that future workers can make a direct comparison between the interpretations presented here and the original mapping. However compilations have been completed in a digital format using Corel Draw version 7.

The mapping of Gustafson (1939) was compiled at 1":100'. As the South Mine was never metrified, all available information for the BHP, Central, South and parts of the British Mine is only in an imperial format. Pre-metric geology from the South, ZC and North Mines, was generally compiled at 1":40'. While this information is extensive, much of the North Mine and ZC mapping was redrafted at 1:500 scale during metrification at the mines. However metrification was not extended to the upper levels of the North Mine and the British Section of the North Mine as these areas were worked out prior to metrification. Wherever possible, any remaining information that has been required from 1":40' scale plans has been redrafted on 1":100 or 1:500 scale work. Details of the geology obtained from lithographs, text figures and monograph plates have been redrafted onto the most appropriate original metric or imperial map sheets. Those interpretations based on modern (metric) mapping are at 1:500 scale. While the scales used in imperial and metric schemes only differ slightly, where direct comparisons between mapping of differing scales has been required, the scales are corrected and scale bars are provided.

Interpretative geological level plans of all major levels in the Pasminco Mine have been compiled at 1:1500 scale using photo-reductions of 1:500 scale geological maps.

In the Pasminco Mine and North Mine, survey plans are compiled at 1:500 scale, 1:250 scale and 1:1500 scale. Geological map scales reflect the available survey department plans with map sheets compiled at 1:500 scale.

Previously, Imperial 1":40', 1":100' and 1":400' scales were used throughout all mines on the Line of Lode following on from the introduction of these scales in the 1930's by the Central Geological Survey.

### A3.5.3. Map Symbols.

Much of the mapping data used to interpret the central, southwestern, British-Junction and some of the northeastern regions of the mining field was carried out during a single massive geological investigation of all mines in the 1930's, which was known as the Central Geological Survey or CGS (Gustafson, 1939). This was a company consortium that aimed to elucidate the geology of the Broken Hill deposit so that future exploration could be accurately targetted and recommendations made for the best targets. Consequently, much of the mapping for key areas of Broken Hill was carried out using a standardised system of symbols and mapping styles.

Members of the CGS went on to found many of the mine geology departments on the field after 1945 and so consequently, geological recording techniques were, at least initially, reasonable similar in most mines. Therefore, the symbols and conventions used in geological mapping in the mines during the 1950's, 60's and 70's did not greatly differ. However variations developed between mines in the 1960's to 1980's as differing philosophies and mining/grade reconciliation requirements began to emerge. Perhaps most importantly, differences in geology of the mineralisation between northeast and southwest began to become apparent and started to influence mining, metallurgical recoveries and so the requirements of geological mapping. The variations in the characteristics of the orebodies of the deposit from southwest to northeast are the main explanation for the significant differences between the emphases of geological mapping in the North Mine and in the Pasminco Mine. These differences are discussed elsewhere.

The reinterpretation of all available mapping of major levels throughout the Line of Lode at one time, a coherent format and uniform approach may reveal structures and other features of the deposit not revealed by interpretative, drill based sections or which are hidden by differing formats, logging schemes, geological conventions and genetic models of their eras.

Essential to this research is that the present geological reinterpretation and compilation was undertaken to interpret existing mapping in a consistent format. Underground geological mapping at Broken Hill was highly variable, with different mines gradually developing very different geological legends, mapping emphases and procedures. Even within a single mine, mapping legends and procedures may have changed over

the years. And within one mine there may have been many generations of geologists who gathered information in personalised ways over many years. So the mapping is variable in detail and quality. With an understanding of the geology of all areas of the deposit it is possible to decipher early geological data and mine records.

#### **A3.5.4. Level Plans Completed.**

The level plans that have been completed during this study are listed in the catalogue on the accompanying CD (Appendix 1).

Geological maps have not been compiled for the Pasminco Mine 22, 23, 24 or 25 (sump) levels. These were active mining and exploration areas at the time of commencement of this compilation and were considered the province of the mine geologists. The Southern Cross area of the 19, 20 and 21 levels has only been interpreted in a general manner for the same reasons.

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## APPENDIX 4.

# UNIT DESCRIPTIONS OF THE WILLYAMA SUPERGROUP

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The following descriptions of the units of the Willyama Supergroup are modified slightly from Willis, et. al., (1983) and Stevens, et. al., (1988). Refer also to the stratigraphic column in Figures 3.5 and 3.6

### **Redan Gneiss**

The Redan Gneiss is the lowermost exposed stratigraphic unit in the Willyama Supergroup and comprises mostly fine-layered albite-hornblende-quartz, +/- clinopyroxene, +/- magnetite rocks and fine-layered Na-plagioclase quartz, +/- magnetite rocks.

### **Clevedale Migmatite**

The Clevedale Migmatite is a 425 m thick basal unit of the Willyama Supergroup and is exposed in two antiformal structures in the Mount Darling Range. It consists mainly of migmatite to migmatitic composite gneisses. Also present are some metasedimentary and other leucocratic quartzofeldspathic gneisses with a quartz-albite - K-feldspar - biotite, +/- cordierite composition. Minor rock types include basic gneiss, rare, thin plagioclase-quartz rock and medium-grained biotite-rich quartzofeldspathic gneiss. Bedding within this unit is thin, discontinuous and frequently disrupted by granitoid and pegmatoid neosome.

### **Thorndale Composite Gneiss**

The transition from the quartzofeldspathic migmatite of the Clevedale Migmatite to the 1000-2000 m thick metasedimentary unit of the Thorndale Composite Gneiss is abrupt, however conformable. The main outcrops of the Thorndale Composite Gneiss are in the Stephens Creek, Mount Darling Range, Mayflower and Oakdale areas. Poor to well-bedded quartz -feldspar-biotite-sillimanite, +/-gamet, +/- cordierite psammitic to psammopelitic metasedimentary composite gneiss makes up the bulk of the unit and is interlayered with subordinate Na-plagioclase-quartz rock and stratiform basic gneiss. Psammitic, psammopelitic and pelitic metasediments are also present. Bedding varies in thickness in both the metasedimentary composite gneiss and metasediments and can be lenticular and/or discontinuous. In the metasedimentary composite gneiss bedding is commonly disrupted by pegmatitic to granitic quartzofeldspathic segregations. Other minor rock types include K-feldspar-rich leucocratic rock and stratiform granular quartz-magnetite and quartz-iron oxide/sulphide rocks.

### **Thackaringa Group**

This group is extensive in the central and southern Broken Hill Block, approximately 1500 m thick, but can range in thickness from less than 1000 m to probably greater than 3000 m thick in the Redan area. The group comprises six formations: the Alma Gneiss,

Lady Brassy Formation, Alders Tank Formation, Cues Formation, Himalaya Formation and the Rasp Ridge Gneiss.

Lithologies of the Thackaringa Group range from quartzofeldspathic compositions to quartz -feldspar-biotite gneisses and leucocratic plagioclase-quartz rocks.

### *Alma Gneiss*

The Alma Gneiss overlies the Thorndale Composite Gneiss conformably and ranges in thickness from 20-50 m in the Champion area, western Mount Darling Range to 1000 m at the Broken Hill airport. It is comprised dominantly of regional scale, lenticular bodies of medium to fine-grained quartz-feldspar-biotite, +/-gamet gneiss with abundant and sporadic, prismatic to augen shaped megacrysts of K-feldspar and plagioclase. This gneiss is also known as 'granitic' gneiss (Slack and Stevens, 1994). There are also megacryst-poor variants in the Champion-Acacia Vale area and in the core of the 'Lakes Creek Structure'. These dominant and variant' gneisses are interlayered with basic gneisses, leucocratic quartzofeldspathic rocks and rare, thin layers/bodies of sodic plagioclase-quartz rock.

### *Lady Brassy Formation*

This generally 300 m thick formation is laterally equivalent to the Alma Gneiss and occurs mainly in the south western Broken Hill Block, Mount Darling Range and the Stephens Creek-Marachi Creek area. It consists of common massive bodies of basic gneiss and well to poorly-bedded leucocratic sodic plagioclase-quartz rocks. These leucocratic rocks exist as massive bodies or as thin to thick interbeds within metasedimentary composite gneiss.

### *Alders Tank Formation*

This unit is generally 200 m thick, but tends to lens out along strike and becomes thin or absent, hence its irregular occurrence in the Broken Hill area and at Thackaringa. At Thackaringa the formation comprises albitic quartzofeldspathic composite gneiss and in the Broken Hill area is characterised by psammitic to psammopelitic composite gneiss. In particular, in the Broken Hill Synform, the composite gneisses are particularly feldspathic and the basal lithology is a garnet-cordierite quartzofeldspathic composite gneiss.

### *Cues Formation*

This 500 m average thickness unit occurs throughout the Broken Hill Block and consists dominantly of psammopelitic to psammitic composite gneisses/metasediments with intercalated basic gneiss bodies. These basic gneiss bodies are continuous in the middle of the formation and thinner and less continuous below this. The basic gneisses are commonly garnet or pyroxene rich with associated thin bodies of quartz -K-feldspar-andesine-biotite-gamet rock (similar to the 'Potosi' gneiss of the Broken Hill Group). The Cues Formation also contains thin, continuous and extensive horizons of leucocratic quartz-microcline albite/oligoclase-biotite±gamet leucogneiss in the Thackaringa, Triple Chance and Broken Hill Synform areas. This leucogneiss has been interpreted by Willis (1982) as a metamorphosed rhyolitic air-fall tuff. Stratiform horizons of granular garnet, quartz +/- magnetite, granular quartz-iron oxide/sulphide, and granular quartz -magnetite rocks are characteristic of the Cues Formation. The sulphide bearing quartz-iron



oxide/sulphide rocks may represent, or be related to, the Broken Hill-type mineralisation that occurs in The Pinnacles- Stirling Vale area.

### ***Himalaya Formation***

This unit is distributed throughout the Broken Hill Block and has a true estimated thickness of 10 -500 m. The main lithology is a well-bedded leucocratic sodic plagioclase-quartz, +/-K-feldspar, +/-biotite rock, which exists either as laterally extensive, thin to massive bodies at Thackaringa or as interbeds within metasediments and composite gneisses at Allendale and in the Mount Darling Range. The plagioclase-quartz rocks have rare scour-and-fill and crossbed structures. Also associated with these rocks are thin to thick (0.5-10m) layered, thinly bedded quartz-magnetite horizons, variably developed interbedded metasedimentary composite gneiss and minor basic gneiss. Towards the base of these plagioclase-rocks pyrite-rich rocks occur.

### ***Rasp Ridge Gneiss***

Varying from 20 m to greater than 700 m, this unit is mainly exposed in a belt from 'Three Gums' homestead through Broken Hill to Stephens Creek. The main lithology is a medium to fine-grained quartz-K-feldspar-plagioclase-biotite gneiss (granitic gneiss), which exists as thin to thick (20-700 m), tabular to lenticular bodies hundreds of metres to tens of kilometres in extent. Variants include those that contain sporadic to abundant garnet and those that are rich in sillimanite. Associated with the gneiss in places are Ba-rich leucocratic calc-silicate rocks, leucocratic quartz-feldspar rocks, 'spotted quartz' rocks and thin, elongate basic gneiss bodies.

### ***Broken Hill Group***

Distributed widely throughout the Broken Hill Block, this group is of the order of 1000 - 1500 m thick and is host to almost all the Broken Hill-type stratiform Pb-Zn-Ag mineralisation, including the Broken Hill ore bodies.

The base of the Broken Hill Group represents a change from dominantly feldspathic composite gneisses of the basal Willyama Supergroup (Clevedale Migmatite, Thorndale Composite Gneisses and Thackaringa Group), to the more pelitic facies of the upper part of this succession (Broken Hill, Sundown and Paragon Groups). Overall the Broken Hill Group is represented by a consistent elastic sequence of pelitic to psammopelitic psammitic sediments, which are commonly garnetiferous and contain zoned calcsilicate nodules.

The Broken Hill orebodies occur within a metasediment-rich part of the Broken Hill Group named the Hores Gneiss. This unit consists of a sequence of felsic metamorphic rocks, which possess chemistry consistent with an origin as a dacite-rhyodacite and which are interpreted as volcano-sedimentary in origin (Willis et al, 1983).

### ***Allendale Metasediments***

This generally 500 m thick metasedimentary unit consists of thinly-bedded pelitic to psammopelitic/psammites and contains minor basic gneisses as well as quartz-gahnite rock, tourmaline-quartz rock and a well-bedded calc-silicate rock (Ettlewood Calc-Silicate Member). The top of the unit is defined by the occurrence of substantial bodies of felsic and mafic gneiss of the Purnamoota Subgroup.

### *Ettlewood Calc-Silicate Member*

This well-bedded fine to coarse-grained quartz-Ca plagioclase $\pm$ clinopyroxene $\pm$ amphibole $\pm$ epidote calc-silicate rock contains high background base-metal values (Pb, Zii, W) and exists as conformable thin (03-10 m), elongate, tabular bodies or pods. It forms an extensive but discontinuous horizon in the Allendale Metasediments, present mainly in the northern Broken Hill Block, Mount Robe-Belmont and Silverton-Thackaringa areas.

### *Purnamoota Subgroup*

This 600 m thick subgroup contains Fe-rich basic gneisses (common abundant garnet or pyroxene), felsic gneiss/rock, 'lode horizon' rocks (quartz gahnite, garnet-quartz rocks), and minor to massive Pb-Zn-Ag deposits, all intercalated with metasediments. The felsic gneisses contain 5-10% mafic minerals (biotite, gamet, magnetite). A variety of felsic gneiss which contains abundant garnet porphyroblasts and/or poikiloblasts is termed 'Potosi' gneiss (James *et al.*, 1987).

Four formations have been identified within the Pumamoota Subgroup (Parnell Formation, Freyers Metasediments, Hores Gneiss, Silver King Formation), of which the Hores Gneiss contains the Broken Hill ore bodies.

### *Parnell Formation*

This is the basal 150-500m thick unit of the Purnamoota Subgroup composed of continuous, widespread pelitic to psammopelitic/psammitic metasediments, intercalated with massive to thinly layered Fe-rich basic gneisses which commonly contain abundant garnet or orthopyroxene. These basic gneisses are associated with lenticular medium-grained quartz-andesine-biotite-garnet +/- K-feldspar gneisses (Potosi gneiss), which become finer-grained quartz-feldspar-biotite +/- garnet gneiss/rock in lower grade areas north of Yanco Glen. The major element geochemistry of the Potosi type gneiss is similar to dacite and less commonly, rhyolites of the calc-alkaline suite, and have hence been interpreted as ash flow tuffs and submarine lavas (Stanton, 1976d; Stevens *et al.*, 1980; Brown *et al.*, 1983).

Small Pb-Zn-Ag mineralisations associated with quartz-gahnite, garnt-quartz and 'banded iron formation' are widespread in the Parnell Formation at places like Allendale, Parnell and Southern Cross mines. Stratiform tungsten mineralisation is commonly hosted by tourmaline-quartz rocks and garnet-epidote-amphibole calc-silicate rocks.

### *Freyers Metasediments*

This unit represents a generally 200-300 m thick (max. 500 m) interval of well-bedded, pelitic to psammopelitic/psammitic metasediments between the Parnell Formation and Hores Gneiss. Beds are thin and planar, however, grading is rare in the metasediments and sporadic calc-silicate nodules occur throughout the formation. Rare basic gneiss and quartz-gahnite and tourmaline-quartz rocks are contained in the metasediments.

### *Hores Gneiss*

This 50-200 m thick rock unit in sillimanite grade areas is comprised mostly of a medium to fine-grained quartz- andesine- Kfeldspar-biotite-garnet gneiss, mineralogically the same as the felsic gneiss that occurs in the Parnell Formation, and is often referred to as Potosi gneiss. The garnets are evenly distributed and abundant. North of Yanco Glen in the lower grade metamorphic rocks, the felsic gneiss can be traced into fine-grained quartz-plagioclase-biotite  $\pm$  K – feldspar  $\pm$  garnet rock/gneiss. However, in some areas such as west of the Parnell mine, the Hores Gneiss is migmatitic and comprises blocks of garnet-bearing felsic gneiss in a coarse-grained irregular granitoid matrix.

The Hores Gneiss also contains variable proportions of intercalated metasediments and is typically associated with minor amphibolite, tourmaline-quartz rocks, which is anomalous in tungsten, and rare quartz-gahnite rock. However, at Broken Hill the formation is anomalously rich in metasediment, consisting mainly of pelites intercalated with lenticular, elongate bodies of quartz-feldspar-biotite-garnet gneiss (Potosi gneiss), minor 'banded iron formation' and the massive stratiform Pb-Zn-Ag sulphide ore bodies of the Main Lode. The ore bodies appear to be laterally equivalent to the felsic gneisses.

### *Silver King Formation*

The Silver King Formation conformably overlies Freyers Metasediments and is laterally equivalent to the Hores Gneiss occurring mainly in the Mount Robe-Belmont area and rarely in the central Broken Hill Block. It is a 300-400 m thick formation comprising pelitic to psammopelitic/psammitic metasediments with abundant amphibole, and lesser amounts of lenticular bodies of quartz-feldspar - biotite  $\pm$  garnet gneiss (Potosi gneiss). In places tourmaline -quartz rocks and minor quartz-gahnite rock exist. Compared with the Hores Gneiss it has a higher proportion of basic gneiss and in the Mount Robe area is massive with common igneous textures, extensive and conformable. The top of the formation marks the abrupt change from basic gneiss to metasediments of the Sundown Group.

### *Sundown Group*

This group ranges in thickness from a few hundred metres to 1500 m and occurs in the central and northern Broken Hill Block. The Sundown Group conformably overlies the Broken Hill Group.

The lithologies of this group are similar to those of the Broken Hill Group but characteristically there are no basic and felsic gneisses nor 'lode horizon' rocks. The group consists mostly of metasediments, with pelitic-psammopelitic rocks together with thinner pelitic rocks more common in the lower half of the group, and psammitic-psammopelitic rocks together with psammitic rocks more common in the upper half. Scattered calc-silicate nodules occur throughout the metasediments. Thin, planar and continuous, well-developed bedding is present in the metasediments and graded beds are common, but atypical. Other rock types include: concordant and discordant intrusive K-feldspar-rich leucocratic rocks, sometimes intermixed with pegmatite (occur abundantly in the Sundown area); rare small basic gneiss and quartz-gahnite bodies near the base of the group; and very rare finely bedded quartz-tourmaline rocks and tourmaline schists also near the base.

## Paragon Group

Outcroppings of this group are extensive in the low-grade Kantappa mine-Brewery Well area of the Broken Hill Block and the Bijerkemo area of the Euriowie Block. The group conformably overlies the Sundown Group and is composed of three formations; the Cartwrights Creek Metasediments including the King Gunnia Calcsilicate Member, the Bijerkerno Metasediments and the Dalnit Bore Metasediments.

The Paragon Group is characterised by graphitic metasediments and also includes spotted and non-spotted phyllites, chialtolite phyllites and schists, albitic psammites and a minor calc-silicate rock.

### *Cartwrights Creek Metasediments*

Graphitic, pelitic to psammopelitic, finely laminated phyllites occur with beds of dark grey to black, chialtolite-rich metasediments in the low-grade Kantappa area. In higher grade areas, such as the Mount Robe-Belmont and Yanco Glen areas, graphitic micaceous psammopelitic schist occurs with sporadic, thick and thin chialtolite-(or sillimanite pseudomorphs after chialtolite) rich pelitic to psammopelitic schist beds. Towards the top of the formation thin to thick beds of fine-grained, grey, laminated, carbonaceous psammite exist. Throughout the formation a few minor horizons of a well-layered, dark-coloured, amphibole-rich carbonaceous calc-silicate rock occur, of which the King Gunnia Calcsilicate Member is one.

### *King Gunnia Calcsilicate Member*

Ranging from 1.5 cm to 50 m thick this laterally consistent calc-silicate rock occurs in the Mount Robe -'Belmont' homestead, Brewery Well, Poolamacca Inlier, Yanco Glen, Silverton and Bijerkerrio areas. It is the most persistent of the several horizons of dark-coloured, amphibole-rich carbonaceous calc-silicate rocks existing in the upper half of the Cartwrights Creek Metasediments. At its type locality near Morning Star mine the layers are dark and hornblende rich, whereas in the Brewery Well area the layers are tremolite – actinolite-rich. Pale layers, rich in quartz and plagioclase, are subordinate. Layers are regular, thin (2-100 mm), planar and continuous with sharp bedding planes.

### *Bijerkerno Metasediments*

Occur extensively in the Kantappa mine-Brewery Well and Bijerkerno areas. and are 700 m thick in the Kantappa mine-Brewery Well area. Fine-grained, pale to grey, feldspathic psammite (albite - quartz  $\pm$  microcline) occurs in substantial quantities and is finely laminated, with sporadic small-scale, high to low-angle crossbeds, flame structures, load casts and rare graded beds. The psammites are infrequently dark grey to black and lenticular. In the low-grade Mount Franks area the psammites are inter-layered with finely laminated graphitic phyllites, in places grading into micaceous psammopelite. In the higher grade Yanco Glen area the psammites are inter-layered with micaceous psammopelitic carbonaceous schists.

### *Dalnit Bore Metasediments*

This unit only exists between Bobs Well and Brewery Well, in the northern Broken Hill Domain, and is up to 700 m thick. It is a well cleaved, grey to black, spotted and minor non-spotted, carbonaceous pelitic to psammopelitic phyllite. Sedimentary structures

are abundant and include fine planar laminae, graded bedding, fading ripples and crossbedding. The phyllite contains rare, lenticular, fine-grained, pale-coloured, interbeds of graphitic feldspathic psammite (similar to feldspathic psammities of the Bijerkerno Metasediments) and also contains locally abundant diagenetic, gossanous, siliceous pods.

# APPENDIX 5. DRILL LOGS – MINE SEQUENCE.

## Appendix 5.1 Log of DDH 7026.

Pasminco Mine, southern lower 2 Lens drilling. A typical intersection of the underwall stratigraphic sequence below 2L ("Lower Lead Lode"), Pasminco Mine (logging by the Author).

Depth (metres)	Lithology	Description
0.0 – 3.0	Pelite tending to Psammopelite (m,z, #g, #s, +/- u)	Very dark grey to black, siliceous Pelite with abundant 1-2mm, sericitised sillimanite bundles throughout foliae. 1-3mm rounded garnets, tending to skeletal occur throughout the first 1.5m and may be overgrowing the foliation. Garnets below 1.5m are slightly larger and tend more to augen shaped. Sillimanite markedly decreases in percentage below 1.6m and the matrix becomes more siliceous.  Calc silicate at 2.5m.
3.0-4.6	Quartz vein.	Prograde foliation dips 55CA. White milky quartz vein with a weak Pegmatite texture and transitional upper contact from 3-4.6m
4.6-8.0	Pelite (m,z,Og, #g, #s, +/- u).	Very dark grey to black, siliceous Pelite with abundant 5-10mm, sericitised and weakly biotite altered skeletal augen garnets  Calc silicate at 5.8m.
8.0-13.3	Psammopelite (s,d, #g, #t).	Pale grey to greenish (in places), Psammopelite which, when strongly altered tends to pegmatite in texture (but retains original banding). Some pegmatitic bands contain coarse grained green, chloritised (?), feldspar or cordierite. 1-2mm spots of biotite occur throughout the interval (after medium grained biotite?), giving the rock a distinctive speckled appearance. Coarse grained, rounded to augen shaped garnets occur throughout but are intensely biotite rimmed and altered in the pegmatitic zones. Prograde foliation (banding), dips 55-60CA at 8.5m, 60,65CA at 12m
13.3-34.3	Psammopelite (s, t, #g, +/- -Og).	Medium grey relatively homogeneous, grainy textured, Psammopelite with a banding defined by minor compositional/textural variations tending towards pelitic and psammitic. The more pelitic bands have an increased percentage of 1-2mm, biotite, sillimanite and garnet (including augen garnets) The more siliceous Psammopelitic bands, tending to Psammitic have only rare very fine-grained garnet and biotite. The bands average 3-4cm wide, are fairly evenly distributed throughout and have indistinct (transitional?), contacts. 2-4mm sericite veins cross cut the interval between 22.5m and 25.5m (0-5CA). The interval is broken between 18 and 20m by 60-65CA joints, filled with pale greenish carbonate?  Below 28.5m, the interval becomes more psammitic with the loss of all pelitic bands. Calc silicates occur at 15.9m (10cm), and 29 6m (3cm)  Prograde foliation dips 65CA at 17.8m, 70CA at 21m, 65CA at 25.2m, 60CA at 30m, 60-65CA at 33m.
34.3-37.7	Retrogressed Psammopelite (s,t,z, #g, +/- .g)/C(z). Psammopelite (s, g, +/- m, +/- z, +/- #g).	Retrogressed, fine grained, siliceous Psammopelite with occasional 2-5cm bands tending to sericite schist (eg: 35.5m 5cm, 35.8-37.5m). Rock typr is basically as in last part of above but has a 45cm band which tends to mafic Potosi Gneiss at 35 35m. Prograde banding dips at 70CA, retrograde shear fabric dips 75-80CA. Fine grained, grey Psammopelite as above (but not retrogressed), and as below 28 5m Prograde banding dips 60CA.
39.5 - 41.0	Pelite (s,m* g->Og).	Dark grey, moderately siliceous Pelite with 0.5-1cm, lensoidal shaped clusters of ragged medium grained garnet. Prograde foliation dips 60-65CA. 1cm calc silicate at 39.8m.
41.0 42.0	Resembles Potosi Gneiss (s->u, #g->O#g)	Rounded red garnet shows weak biotite alteration and partial rimming in places

42.0 44.7	Psammopelite (s->u,g,+/-m,+/-z,+/-#g).	Fine grained, grey Psammopelite as at 37.7m, and below 28.5m. Some milky blue quartz impregnates some 5cm bands and has some red 2-4mm garnets associated with it (resembles PG). Prograde banding dips 60CA. Broken from 42.6-44.2m.
44.7 50.4	Broken Pelite (s,g>Og,Og,z,+/-e).	Dark grey to black pelite with strongly silicified matrix and moderate amounts of very fine grained sericite in some bands. Zones of sericite alteration are all strongly silicified and in some places have 1-2mm lenses of soap green epidote (?). Garnets occur as spotty, medium grained crystals and as 0.5-1cm wide lensoid clusters of medium grained crystals. Some coarse grained augen garnet is also present. Very broken, especially from 45m-46.5m, 47.8m-47.95m, 48.5m-50m. Breakage seems to be a result of foliation parallel and low angle jointing intersection. Prograde banding dips at 60CA at 47m, 50CA at 50m.
50.4-63.6	Psammopelite (s,g,#g,+/-*g,+/-m,z,e).	Mostly homogeneous, light grey, siliceous Psammopelite with fairly common 1-5cm, pelitic bands which contain most of the coarser grained garnet. These Pelite bands tend to have fairly indistinct, though definite contacts. Definite calc silicates occur at 52.9m (3cm), 55.5m (7cm), and 59m (2cm). A large part of the entire interval between 55.5m and 59m has a pale greenish tint, similar in colour to the calc silicates. This interval may have a significant calc silicate component in it's mineralogy (some "ghosts" of calc silicate bands around 3cm are present within this interval). Prograde banding dips 55CA at 51.6m, 70CA at 57.3m, 65CA at 59.5m and 50-55CA at 63m. The interval becomes badly broken below 61.8m.
63.6-65.6	Pegmatite (s,dd,x,+/-#g,+/-t).	Fine grained, black, fine grained garnet spotted Pelite becomes increasingly common below 62.4m Light grey to greenish Pegmatite with common speckling and splotching of medium green siliceous chlorite (after feldspar or cordierite?). Quartz is milky blue in colour.
65.6-69.1	Spt Psammopelite (s,t,dd,0#g,Og,z)->resembles Potosi Gneiss	Finely banded, with a moderate, siliceous sericitised fabric in first 80cm. Composite Psammopelite with abundant, weakly boudinaged Pegmatitic bands to 3cm. These often have weakly sericitic and siliceous feldspars (pale greenish). Rounded red garnets are common in the mafic bands and to a lesser degree in the Pegmatitic bands. Where mafic bands are thin the garnets tend to be more lensoidal and augen-like. Clear quartz tends to bluish throughout, especially towards the base of the interval. 2-4mm sericite veins at around 10CA occur at 66m. Prograde banding dips 50CA at 66m, 45CA at 68.8m.
69.1-79.2	Psammopelite(.g,s,+/-z)-> Garnet Quartzite (t).	Very finely banded, homogeneously textured Psammopelite. Fine biotite and filamentous sericitised sillimanite define 1-3mm foliae with less mafic bands of the same width in between. Grey feldspar Pegmatite bands up to 20cm are common from 72m-73.7m. Fine garnets are spotted throughout the interval and appear to overgrow the foliation. Prograde foliation dips 25CA at 71m, 35CA at 72m, 30CA at 74m, 20CA at 76m (A strong, retrograde axial planar foliation cross cuts the prograde banding and produces a chloritic foliation within a Pegmatite band at 76m. It dips at 15-20CA in the opposite sense to the prograde bands). 35CA at 76.5m, 50-15CA between 76.55-76.7m (asymmetric fold hinge), 55-60CA at 77.1m, 85CA at 78.6m. Garnet becomes finer grained and relatively more common with depth. The rock begins to tend to biotitic Garnet Quartzite below 73m.
79.2-79.6	Lode (u,#j,g,+/-z,sp,+/-cp,gl,+/-as)	Narrow, Pegmatite textured blue quartz, lode vein. Sharp lower contact and diffuse upper contact. Most garnet is wall rock derived. Lower contact dips 70CA (parallel to prograde banding in next interval). Sericite in gahnite.
79.6-85.6	Garnet Quartzite tending to Psammopelite (t,+/-u,+/-z,+gl,cp,po) interbanded with Garnet Quartzite (t,s,u,z)	Fine grained, banded, biotitic Garnet Quartzite with some patches of galena bearing blue quartz (sometimes veinlets). From 79.6m-81.3m, the rock tends to Psammopelite with zones of fine, wispy to lensoidal sericite foliae. Some 2-3cm, sericitised Pegmatite segregations are also present in this upper, transitional zone. The interval is moderately broken in the first 1.3m. Retrograde fabric dips 65-70CA at 80.6m. Prograde banding dips 70-75CA at 79.8m, 65CA at 80.7m, 70CA at 82m, 35-45CA between 83.3-83.5 (asymmetric fold?), 40CA at 85.5m. 85.6-90.6
85.6-90.6	Spotted Pelite (.g,s,+/-z) - Garnet Quartzite(t)/Pegmatite (nd,po,cp,gl).	Very finely foliated, lack, homogeneously textured Pelite with a moderately siliceous matrix and common 2-10mm blue quartz stringers (especially in the first 3m. Fine biotite and rare filamentous sericitised sillimanite define 1-3mm foliae. A coarser banding is defined by varying relative abundances of matrix quartz and biotite. Green feldspar
	Pegmatite	Pegmatite bands occur at 87.8m (60cm), 88.6m (20cm). Grey feldspar pegmatite bands to 13cm occur between 87-87.5m. to 20cm are common from 72m-73.7m (possibly altered green feldspar types). Fine garnets (0.5-1mm), are very common and are spotted throughout the interval. These garnets become slightly coarser grained below 89m (1-2mm). They appear to overgrow the foliation. Prograde foliation dips 40CA at 86m, 35-40CA at 87.6m, 40-45CA at 89.2m, 35CA at 90.2m.
90.6-95.0	Potosi Gneiss (s,t,0#g->Og,+/-m,+/-z).	Coarsely garnet spotted, light grey, strongly felsic banded Potosi Gneiss. Garnets are generally around 3-7mm and are weakly biotite altered. Prograde banding dips 40CA at 92m, 30CA at 93.5m and 35-40CA at 95m.
95.0-100.9	Pelite	Fine grained, black, garnet spotted Pelite, with garnets ranging from 0.5mm (most



	(t,g,#g,m,z,s).	common), to 2mm. Most garnets appear to be sericitised to some degree. Pegmatite segregations (grey feldspar), are fairly common throughout and range from 1cm to 8cm widths (approximately 10-15% of the interval). Some Pegmatite has patches of green chlorite. Broken from 97.5-100.5, by low angle joints (30CA, cross cut banding). Sillimanite occurs as very fine wispy, white streaks on the foliation planes and is variable in abundance.
100.9-110.3	Psammopelite (t,s-u,g->#g,m,d) interbanded with Pelite (t,z,g->#g).	Interbanded dark grey, tending to black Psammopelite with definite but indistinctly defined coarse banding and biotite/sillimanite rich, pelite (approximately 60%/40%). A fine Granular "pepper and salt" texture occurs throughout and is caused by 0.5-3mm, spotty to lensoid biotite clots. Very fine garnet, and 0.5mm, lensoid sericitised sillimanite bundles also add to this texture. Sillimanite is variable in its distribution and can be a major component of the more Pelitic, less silicified bands. Prograde banding dips 55CA at 102.4m, 65CA at 104m, 65CA at 105.5m, 70CA at 107m, 65CA at 108.5m, 70CA at 110m
110.3-111.6	C(z,s)/Pm.	Two discrete bands of intensely sheared, siliceous, sericite schist occur at 110.3m (20cm) and 111.15m (60cm). Psammopelite, interbanded with Pelite as in preceding interval, but only weakly retrogressed in discrete, sub centimetre planes and in a weak zone from 111.75m-112m. Shear fabric dips 75CA. Prograde banding dips 70CA. Shear zones have sharp contacts.
111.6-115.6	Pelite(t,s,z,g->#g,m,d) interbanded with Psammopelite.	As at 100.9m, but with a more homogeneous texture (less differentiation between bands), and a composition tending more to pelite. Dark grey to black very siliceous (silicified?), pelite tending to psammopelite with definite but indistinctly defined coarse banding which is defined by variations in the amounts of quartz, biotite, and sillimanite (sericitised). A fine Granular "pepper and salt" texture occurs throughout and is caused by 0.5-3mm, spotty to lensoid biotite clots. Very fine garnet, and 0.5mm, lensoid sericitised sillimanite bundles also add to this texture. Sillimanite is variable in its distribution and can be a major component of the more Pelitic, less silicified bands. Prograde banding dips 80CA at 113m, 65CA at 114.6m.
115.6-116.2	Pelite (z,t,Og).	Fibrous, sericitised, sillimanite rich pelite with common 0.5-1cm augen garnets. Prograde banding dips 65CA.
116.2-116.6	Retrogressed Pelite tending to retrograde shear (z,s).	Pelite as above, but intensely retrogressed and sheared. Retrograde shear foliation dips 50CA.
116.6-116.8	Pelite (t,s,*,g,g,d).	Coarse garnet spotted, biotitic contact phase of amphibolite (below). No magnetite. Banding dips at 45CA.
116.8-117.7	Amphibolite (as,t,mt,s,+/-g)	Strongly magnetic, finely banded amphibolite. Banding is less well defined away from contacts. Some coarse grained, rounded to ragged garnet overgrows the contact banding near the upper boundary. Biotite becomes more common with depth.
117.8-118.1	Amphibolite (as,t,s,+/-g).	Banding dips 40-45CA
118.1-122.9	Pelite(t,s,z,g>#g,m,d) / Psammopelite	As above but non-magnetic and possibly more biotite. Banding dips 50-55CA. As at 111.6m Prograde banding dips 80CA at 119.3m, 80CA at 120.8m, 80-85CA at 122m.
122.9-123.6	Pelite (m,z,t,g,s).	Whitish grey, stripy textured, sillimanite rich pelite. Sericite after sillimanite is common.
123.6-125.0	Pelite (t,mt,g) with BIF(mt,s,g,+/-cp).	Interval is dominated by strongly magnetic pelite that is texturally almost identical to the preceding. Two narrow bands tend to Garnet Quartzite & are strongly magnetic. These occur at 124.3m (5cm), and 124.4m (5cm) and are probably coarsened BIF. A third band at 123.2m (7cm), is non magnetic. BIF bands occur at 123.86m (17cm), 124.27m (5cm), and 124.94m (13cm)

## Appendix 5.2. Drill hole log of DDH 7490

Pasminco Southern Leases, mine section 292. This drill hole passed through the majority of the mine sequence from the hanging wall (Hangingwall Quartzofeldspathic Gneiss) to the Rasp Ridge Lode Horizon, proximal to the Footwall Quartzofeldspathic Gneiss. This log provides a detailed description of the lithologies of the mine sequence in a position distal to the orebodies. The descriptions provide details of the stratigraphic units and the variations in rock textures.

Compare this log with DDH 3355 (below) from the Pasminco Northern Leases that also passed through the same Mine sequence rocks. Logging by A. E. Webster.

**HOLE No: 7490      LOGGED BY : T. Webster**  
**LOCATION: Pasminco Mine Southern Leases Section 292**

FROM	TO	DESCRIPTION
0.0	26.5	No Return
26.4	33.0	Pe(m,0g,mOg,mOd,*g) Moderately matrix oxidised (kaolin?) pelite with abundant prismatic sillimanite within lenticular & flame shaped, anastomosing fibrolite foliae. Sillimanite is mostly present within biotite-rich foliae. Most garnets are present within felsic segregations (pegmatites) & are strongly oxidized to goethite. Several bands of clustered 1-2cm, ragged lenticular garnets also occur. Goethitic feruginisation is associated with oxidation along all fractures & pegmatitic segregations. Most flame shaped & lenticular fibrolite bundles are retrogressed to sericite. Feldspars are rounded to lenticular & form light grey bands or lenses throughout interval. (white).  Peg bands most common from 30.2m-32.7m  Prograde foliation dips 54CA at 28m, 45CA at 32m. Most fracturing parallels foliation.
33.0	37.0	?/Pe (m,m*g) Two major & one minor band of matrix oxidised, finely banded, very fine-grained to fine grained amphibolite with narrow bands that tend to BIF or calc-silicates (non-magnetic). These are interbanded with sillimanite-rich pelite as seen in the preceding interval  32.9-33.4 Very fine-grained, finely banded Amphibolite.  34.3-34.9m Very fine-grained, finely banded Amphibolite with minor coarse grained garnet in felsic bands.
37.0	41.2	bdd Anorthositic rock->A/A (.g,t) Very fine-grained, finely banded & massive, medium to dark green rock with common, very fine-grained garnet. Strongly banded from 37-37.9m. Puggy & sheared from 37.2-37.6m & 37.9-38.9m. S0 banding dips 60CA at 38m. Massive from 39.2-41.2m.
41.2	57.3	Pe(Od,m,*g,m*g)/Pm->Ps 90% 10% Medium grey, variably psammopelitic pelite with common 1-5cm, ragged clots of red garnet (associated with pegmatitisation) & abundant 0.5-1cm, augen feldspars. White sillimanite bundles are common & mostly very ragged to flame shaped (weakly retrogressed). Occasional bands of psammite to psammopelite to 2cm in places. S1 foliation dips 45CA at 48m, 47CA at 54m, 40CA at 56.6m
57.3	61.1	A(+/-g,t) Very fine-grained, medium to dark green amphibolite that is very similar in texture to that at 40.1-41.2m. A very weak foliation is defined by biotite & fine felsic minerals & dips 60CA at 61m. Sharp contacts.
61.1	62.9	Peg/Pe(m*g,m,s, g) 60% 40% Pelite as at 41.2m (moderately matrix silicified & pegmatitised) in first 70cm. Medium grained aplite or quartz feldspar porphyry occupies the rest of the interval. Porphyry possibly banded in last 50cm.
62.9	71.2	Pe/A

- 71.2 75.2 Pe->Pm(\*g,mOg,m,s)/Ps(s,+/-m\*g)  
Moderately matrix silicified pelite with common, very coarse-grained ragged garnets associated with blobby, lenticular pegmatitic segregations. Many asymmetric mesoscopic folds. 73.7-75.2 Interval weakly resembles potosi.
- 75.2 82.4 rPG(m, m\*g,#g)/CS  
Strongly foliated Potosi Gneiss with a well-developed foliation defined by foliar bundles of white fibrolite (weakly sericitised).  
Four bands of greenish pink calc-silicates from 8-10cm wide occur within the interval. As calc silicates end, so does potosi-like rock.  
77.3-78.2 Ps (.g). Fine-grained, glassy psammite.
- 82.4 89.9 Ps(t,a,+/-j)->CS/PG(#g)->GG  
Interbanded fine-grained glassy, dark-grey to pinkish or greenish psammite which variably tends to calc-silicate & or amphibolite. The psammite is finely banded with some coarse-grained garnet in felsic segregations. Trace gahnite in some segregations?  
PG->GG 8 bands of massive to weakly banded, very felsic potosi->granite gneiss with common blobby to well-rounded garnets. Largest band at 87.4-89.9 & is strongly banded & potosi-like (some sillimanite).
- 89.9 98.0 Pe->Pm(mOd,m,m\*g,m\*t)/Ps(s,u,t,+/-m\*g)  
Moderately foliated, biotite speckled pelite with 2-4mm feldspar augen & common 2mm ragged biotite clots (after garnet). Biotite clots often form bands. Fibrolite defined foliae to 2mm wide. Bands of very fine-grained psammite (as at 82.4m) are interbanded with pelite & average 4-10cm & are most abundant from 89.9-93.6. Largest psammite = 89.9-90.9m. Biotite spotted pelite remains dominant below this interval.
- 98.0 101.8 Pe->Pm(mOd,m,m\*g,m\*t)/L(u,\*g,j,+/-z)->Peg/Peg(d,z,+/-g, u,j,t)  
Pelite tending to psammopelite as in preceding interval. Two bands of pegmatite are present in the interval & are moderately to strongly blue-quartz altered at the margins. Coarse ragged red garnets are associated with the blue quartz as are 'books' of dark biotite. Centres of pegmatites are white, strongly silicified & sericitised (hydrothermally?) after myrmekitic feldspar. Pegmatite band at 101-101.8 is totally blue quartz altered with common gahnite at feldspar crystal boundaries.
- 101.8 112.8 Pe->Pm(mOd,m,0g,.g,t)/Ps  
Schistose pelite to Psammopelite (similar to 89.9m), with bands of coarse grained garnet augen where the matrix is pegmatized. 4mm lenticular clusters of fine-grained garnet & biotite (after garnet) are common. Larger garnets are biotite altered to varying degrees. Larger garnets associated with pegmatite segregations. 2-5cm, glassy psammite bands (->CS) are common. Fibrolite common as 1-3mm foliae.  
102.3-107.3m. Badly BROKEN. 5-10CA with chloritic fractures
- 112.8 140.8 resPG(Og,t,x,m,z)  
Strongly biotite-altered potosi gneiss. All garnets are strongly biotite altered & skeletal, giving the rock a distinct mottled appearance (pepper & salt).
- 140.8 153.7 Pe(\*g,m,Og,+/-t)->cPe  
Coarse-grained lenticular, ragged-garnet rich pelite. Very biotite rich with 1-3mm lenticular fibrolite foliae. Ragged 2cm-80cm (average 10cm) pegmatitic segregations with pinnitised cordierite (dark green clots).
- 153.7 162.3 Ps->Pm (d?.g,#g,m,z)  
Milky (feldspar altered?), medium grey psammite with common 1-5mm bands of more pelitic material containing medium grained garnets. Fine garnets are common throughout the psammitic material. Occasional streaks & lenticular to flame-shaped bundles of fibrolite (sericitised) are common in more pelitic bands. Some pegmatized patches.
- 162.3 199.1 Ps(d,.g,m,z,t)/Pe->Pm(m\*g,m,ser) 80% 20%

Interbanded, milky, pale to light grey psammite with common, very fine-grained garnets & strong feldspar alteration (milky white overprint) which tends to pegmatization in places & 3-10cm bands of more pelitic, fibrolite-rich pelitic material with 2-4mm, rounded to skeletal garnets. White fibrolite bundles appear retrogressed but contain some fine needles of sillimanite (S3?). Interval tends to composite psammite in places & garnet spotted pegmatitic bands are common (2cm-70cm)

199.1 205.3 Pm(mOd,m,z,mOg)->Pe

Medium grey pelite with very well developed 2-4mm wide fibrous, white, anastomosing, lenticular to flame shaped fibrolite foliae & common, rounded, 3-6mm, skeletal, biotite altered garnets. Fibrolite wraps feldspars. Biotite & fibrolite give the rock a distinctive stripy & spotted texture. Matrix is very fine-grained & quartzofeldspathic. Some 0.5-1.5cm bands of fine-grained, quartzofeldspathic psammite are present. Coarse, garnet bearing pegmatitic bands from 5cm to

205.3 219.7 Pm(mOd,d,g,g,m,z)

Fine-grained, medium grey, milky, quartzofeldspathic psammopelite that is variably pelitic & psammitic. Pelitic bands are rich in 1-2mm, fine, white, fibrous fibrolite (weakly retrogressed) that form a fine foliation that tends to anastomose around 3-4mm, augen feldspars. 1-2cm milky, pale grey quartzofeldspathic psammitic bands are common throughout the interval & contain abundant, very fine-grained garnet (causing pinkish colour). White fibrolite foliae give rock a distinctive striped appearance when present. 1-5cm pegmatitic bands are present throughout interval.

211.5-216 Pm(m) Moderately pelitic & rich in fibrolite bundles.

216-219.7 Pm (d,g)->PG Interval becomes strongly quartzofeldspathic, tending to Potosi Gneiss in last three metres.

219.7 232.2 A(px?,+/-s,u,t,m\*g)/g,u,t UNIT 4.4

Massive, fine-grained, olive green amphibolite, which is interbanded with a coarse-grained garnet, dominated rock with a blue quartz matrix & coarse clots & patches of black biotite (Bog rock). Dominant component of amphibolite is a pale olive-green to khaki coloured mineral resembling pyroxene (i.e. not amphibole). First 1.5m & last 2.5m of interval is a hybrid rock type consisting of abundant, skeletal garnets overgrowing the fine grained, olive green amphibolite.

232.2 243.4 SptPm(Og,u,t,+/-m\*t)->PG UNIT 4.4

Massive to weakly banded, strongly siliceous rock with abundant, rounded, 2-4mm, variably skeletal & biotite altered garnets. Variably resembles spotted psammopelite. Black biotite is most abundant in the first five metres but diminishes below. Milky blue quartz becomes more common below 327.5m & dominates the matrix in the last metre. Garnets become less common with depth but are still common in last metre. Most Potosi Gneiss-like in last three metres.

243.4 248.8 Pe(m\*g,m\*d,t,z)

Granular textured pelite with common, variably ragged 1-2mm garnets & small clots of white feldspar? Entire interval is speckled with ragged, 1-2mm black biotite. Combination of garnets, biotite & feldspar clots gives the entire interval a strong pepper & salt texture. Moderately broken parallel to schistosity.

248.8 346.0 Ps(g,d,+/-m,z)/Pe(m,z,g)->Pm 60% 40% UNIT 4.5

Interval of light-grey milky psammite dominated, fine-grained garnet rocks with common, variably pelitic to psammopelitic bands throughout. A number of larger, well developed pelitic bands & two moderately well developed shear zones are also present (see entries below for major zones). 2-15cm wide pelitic to psammopelitic bands with 1-3mm wide 'streaks' of fibrolite foliae are ubiquitous & tend to cluster together in broader (to 2.5m) bands

283-285.5. brknPe(m,g)->C(z,t). Badly broken, sheared interval of pelite.

324.4-326.1 Pe(z,g)/brknC(t,z)/PUG 1 metre of well developed, dark grey pelite with strong sericite followed by a strongly broken & puggy remainder. Fracture planes sub-parallel to foliation & chloritic.

346.0 347.3 Pe(z,t,g)/Pm(g).

Medium grained, granular textured pelite with common biotite speckling & 0.5-1cm bands of psammopelite in places. Sillimanite all strongly retrogressed, consisting of fine lenticular bundles

347.3 382.5 Pe(Od,z,m\*g,g)/Ps(g,t) 65% 35%

Dark grey, fibrolite (sericitised)-rich pelite with an anastomosing foliation defined by wispy white, fibrous fibrolite foliae & biotite. Interbanded with pelite are many bands of massive, light to pale milky grey psammite with 0.5-2mm, ragged black biotite clots which give it a speckled appearance. Pelite becomes more abundant with depth. Clear feldspar augen are very common within pelite from

366m. Fine fibrolite foliae wrap the feldspars.

- 382.5    395.1    Ps(s,t,m\*) UNIT 4.5  
Massive, pale bluish grey to pale grey, strongly siliceous psammite with variable numbers of 0.5-2mm, black biotite clots & specks. Similar to many psammite units in previous interval.
- 395.1    409.7    Pe(m,z,mOd,t,m\*)->Pm UNIT 4.5  
Well developed augen feldspar pelite with abundant lensoidal, translucent grey feldspar augen. Well-developed schistosity defined by white fibrolite & biotite with medium & fine-grained garnets is variably developed & gives the rock a moderate to strong 'fishscale' texture. Some bands of finer grained, more psammitic material with poorly developed foliation in places.
- 409.70    414.10    Ps(s,g,+/-m,z,j) UNIT 4.5  
Very pale milky grey to pinkish psammite with a dusting of very fine garnet & bands that contain some fine biotite & wispy fibrolite foliae. 2-4mm greenish bands may be gahnite.
- 414.10    434.00    Ps(s,g,t,m\*)/Pe(Od,m,z,g) 70% 30% UNIT 4.5  
Interbanded, fine-grained, massive, pale-grey, biotite speckled psammite & medium to coarse-grained, feldspar augen pelite. Pelite bands average 40-60cm & contain translucent grey feldspars of variable size (around 1cm). Fibrolite foliae wrap feldspars & become knotty in places.
- 434.00    447.00    Pe(Od,m,z,g) UNIT 4.6  
Strongly developed feldspar augen pelite with 0.4-1.2cm translucent grey feldspars throughout. Feldspars are wrapped by fibrolite-biotite foliae (sericitised) & sometimes have sericite halos. 0.5-1.5mm garnets form a part of the schistosity. Very fine garnets dust feldspars. Strong 'fishscale' texture throughout interval.
- 447.00    468.60    sptPm(\*g,m\*g,m,z,d)/+/-L(u,po,cp,sp,+/-gl)  
Strongly developed, dark grey spotted Psammopelite with abundant 3-6mm, ragged, skeletal red garnets & common, wispy, lenticular to fibrous bundles of weakly retrogressed fibrolite. 0.5-1cm pegmatitic segregations are common & often contain traces of chalcopyrite & pyrrhotite. Mineralised blue quartz bands are common in places (see assays from main intervals).  
  
463.5-464.3. L(u,g,m\*g,j,po,cp,+/-sp)
- 468.60    497.30    sptPm(m\*g#g,d,m,z)/L(u,+/-j,po,cp,+/-sp)  
Medium pinkish grey spotted psammopelite with abundant 1-3mm garnets throughout. Garnets are slightly less abundant than preceding interval & much finer grained. Interval is also much less mafic (less biotite) & richer in feldspar in the matrix. Garnets cluster to define very ragged 0.5-2cm bands. Occasional faint, wispy, hair-like foliae of fibrolite occur in places (sericitised). 2-6cm pegmatitic segregations are common & roughly parallel to fibrolite foliation.  
  
L(u,j,+/-g,z,po,cp,+/-sp) Stringers & bands of blue quartz-gahnite mineralisation occur in places & occasionally carry sphalerite (e.g. 484.9m). They range from vaguely defined 1-2cm bands to well defined 10-12cm bands (see assay intervals). Some cluster together.
- 497.30    518.60    sptPm(s,d,#g,g,+/-\*g,+/-z)->PG/PG(s)  
Moderately developed, strongly quartzofeldspathic light milky grey spotted psammopelite with common 1-2mm garnets & occasional 2-4mm garnets. Coarser garnets are moderately to weakly biotite altered. Vague gneissosity defined by garnet (& biotite) abundance but interval tends to massive. A very fine, wispy, hair like fibrolite foliation is present (sericite). Texture is transitional between spotted Psammopelite & Potosi Gneiss with the spotted psammopelite texture predominating. Minor bands tend more strongly to Potosi Gneiss. 5-15cm pegs common.  
  
506-507.9m PG(d,\*g,s,t). Strongly felsic, light grey, well developed, massive Potosi Gneiss. Biotite speckling after garnet & moderate alteration of coarse garnets.
- 518.60    526.10    PG(m\*g,m\*t,+/-z,m)+/-cp,po  
Well developed Potosi gneiss with fairly common 1.5-3.5mm garnets which are skeletal & weakly biotite altered. 1-2mm, ragged, black biotite clots are also common (after garnets) & give the rock a speckled appearance. Some dark biotite also defined 1-3mm foliae. 0.5-15cm peg segs are common. Weakly retrogressed & sheared in 2-5cm planes towards base. More mafic with only 1-2mm garnets in last 2.5m (tends to spotted Psammopelite). Trace sulphides in some fine pegs.

- 526.10 545.80 mod shrd PG(t,mOg,z)/C(t,z,x,+/-g)  
Moderately sheared, well-developed Potosi Gneiss with a moderate to strongly developed, shear derived biotite & sericite defined schistosity. 1.5-3mm garnets are all weakly flattened parallel to the foliation & are strongly eye-shaped. Shear schistosity wraps augen. Schistosity strongly effects pygmatically folded pegmatitic bands which are folded parallel to the schistosity.
- 529.7-530.6 C(t,z,x). Intensely developed plane of biotite-sericite schist with knife-edge contacts. Dips 10CA (parallel to schistosity in potosi).
- 545.80 562.80 mod shrd sptPm(.g,mOg,t,z)/+/-L(u,ser,j,po,cp)  
Moderately sheared, biotite-rich spotted psammopelinite with abundant 0.5-2mm garnets & a moderately developed shear-derived schistosity, which dips 30CA. Intensity of shearing diminishes with distance from uphole contact. S1 fabric is at a very low angle to CA (S1 = 10CA, FOLD HINGE ZONE?). Weakly sheared in last 4m.
- 562.80 576.00 wk shrd Pm(s,g,z,m\*t,+/-j)+/-po,cp/L(u,z,+/-po,cp,sp)  
Fine grained medium grey Psammopelinite with common fine-grained garnet & a moderate, sericitic schistosity (shear-derived) which dips 25CA. Texture is similar to following spotted Psammopelinite interval but contains less garnet, is finer grained & garnet is much less common. S1 low angle to CA FOLD HINGE?
- 565.3-566.7 L(s,u,z,+/-sp)->Peg(u). Massive pale bluish quartz lode with streaks of dark brownish sphalerite in sericitic fractures. Most fractures strongly sericitic. Possibly extensively silicified & mineralised pegmatite.
- 573.4-574.2m. L(s,u,z,+/-po,cp)->Peg(s,u). Weakly mineralised, siliceous lode probably derived from altered pegmatite.
- 576.00 598.80 sptPm(mOg,0g,t,z)/L(u,z,j)po,cp,sp,+/-gl  
Well-developed, strongly biotitic spotted Psammopelinite with abundant 3-4mm, rounded garnet porphyroblasts. A weakly to moderately developed, shear-derived retrograde foliation is pervasive & all narrow bands of pegmatite are strongly sericite & quartz altered (fine-grained saccharoidal, metahydrothermal?). Fine fibrolite (now sericite) & biotite define a strong S1 schistosity. Stringers of weakly mineralised bluish quartz tending to pegmatitic lode are ubiquitous.
- 587.5-588.2m. HG(u,s,j,z,+/-g,sp,po,cp). Band of high-grade well developed siliceous lode with 20cm of very high-grade, sphalerite-dominated durchbewegt mineralisation (with ragged to rounded quartz clasts).
- 592.9-593.9m. Peg(s,z,+/-g,+/-t) Intensely sericitised & silicified, pale greenish cream coloured pegmatite.
- 598.80 613.10 wk shrdPG(m\*t,\*g,u)/mod shrd cPm(.g,z,s)->sptPm  
Well developed, medium blue grey Potosi Gneiss with a weak shear-derived foliation defined mostly by biotite with some sericite. 1-2mm garnets are all now dark biotite. Coarser garnets are weakly biotite altered. An interval of pegmatite-rich, weakly sheared Psammopelinite to spotted Psammopelinite occurs from 605-608.8m. The lower interval of potosi is slightly more strongly affected by the biotite-defined foliation.
- 613.10 618.30 rPm(.g,mOg,z,s,j)po,cp,+/-sp/MG(s,u,j,+/-z,sp,po,cp,+/-gl,py?)  
Fine-grained Psammopelinite with common fine grained garnet & abundant fine, hair-like sericite (after fibrolite). 0.5-1cm bands of fine-grained gahnite are common & generally contain minor amounts of ore sulphides (mostly pyrrhotite & chalcopyrite) Texture is similar to the spotted psammopelinite in the next interval The interval is strongly mineralised (silicified & 'gahnitised' from 615.6-618.3m with four bands of coarse marmatite from 1.5cm to 4cm wide. Mineralised intervals (especially sphalerite-rich parts) seem to be localised on intensely silicified & altered pegmatite bands
- 618.30 638.70 sptPm(m\*g,z,\*t)/L(s,u,j,sp,po,cp,+/-gl,as)/Peg(nd)  
Well developed, dark grey to reddish black, spotted Psammopelinite with many 0.5-1.5cm variably mineralised lodey stringers. Common Peg segs have green feldspar.
- 627.1-629.3. MG(u,j,z,sp,po,cp,+/-gl,as). Very strongly developed interval of blue quartz mineralisation with a 1m band of massive, light milky blue quartz lode with abundant well-formed gahnite crystals from 628.2-629.2m. High-grade sphalerite dominated durchbewegt mineralisation from 627.1-628.1m. Mineralisation possibly focussed on intensely altered pegmatite bands

- 638.70 655.20 Pm(.g,d,z,m)/L(s,u,j,z,-g,co,po,+/-sp)  
 Dark pinkish grey, fine-grained-garnet psammopelite which is texturally similar to preceding spotted interval. Fine garnets are abundant & 1-12cm, sericitised pegmatite intervals are common & occasionally carry green feldspar. Occasional ore-sulphide bearing stringers are present. Psammopelite is strongly quartzofeldspathic compared to the spotted intervals preceding it.  
 639 9-646.6m. L->sptPm(s,u,g,z,j,po,sp,cp,+/-gl).  
 Intensely mineralised interval of garnet psammopelite, with abundant pegmatitic segregations. All pegs carry mineralisation & are variably blue quartz & gahnite altered 1cm sphalerite stringer at 641.3m Strongly developed blue quartz-gahnite lode from 642-643.3.
- 655.20 668.90 Pm(.g,m\*g,z,u,d)/Pm(u,mOg)->PG  
 Fine-grained quartzofeldspathic psammopelite similar to preceding interval but with less garnet & common, hair-like fibrolite foliae (now sericite) which parallel a poorly defined gneissosity (garnet & feldspar abundance). Fibrolite bundles become thicker & more common below 662.5m. 0.5-5cm Pegmatitic segregations are common. Several bands tend to blue quartz-rich, massive Potosi Gneiss in texture (e.g. 661.5-662 5).
- 668.90 669.90 GQ(s,u,po,cp)  
 Strongly brecciated, metasomatically derived, light pinkish to orange fine-grained garnetiferous rock. GO rock in Pasmenco North terminology. NOT TRUE GARNET QUARTZITE. Some banding is preserved but much of interval is open framework jigsaw breccia with quartz deposition around fragment margins paralleling fragment edges. Matrix is mostly pale, milky blue quartz. Ragged splashes of pyrrhotite & a single splotch of marmatite occur in silicified psammopelite at 669m.
- 669.90 676.00 Pm->Pe(s,u,z,g)/PG(mOg,t) UNIT 4.7  
 Medium grey strongly sericitic Psammopelite with common fine-grained garnets. Fibrolite bundles tend to knotty or flame shaped & occur in more pelitic zones They are all sericitic. Psammopelite becomes well developed Potosi Gneiss over 30cm transition. Last 2.3m of interval = massive, coarse-garnet spotted Potosi Gneiss with common 0.5-1mm biotite specks after garnets.
- 676.00 679.60 brknPe(\*g,z,s,g)/Peg(z,s)+/-cp+/-PUG UNIT 4.8  
 Strongly sheared black pelite with very coarse porphyroblastic garnets. Interval appears to have been moderately metahydrothermally sericitised. Shear & fracture planes dips 45CA. S1 schistosity dips 26CA. Minor chalcopyrite specks in sericitic & silicified pegmatites.
- 679.60 786.20 Ps(d,g,+/-z)/Pe(0d,m,z) 65% 35% SUITE 5  
 Mainly monotonous sequence of interbanded fine-grained, pale milky-grey psammites with a fine dusting of garnet & 1-20cm bands of fibrolite & sillimanite rich pelite. The pelite is variably feldspar augen-bearing & these augen become more common below 730m. Strongly developed needle-like sillimanite (S3) clusters are associated with many augen bearing pelite bands & appear to post-date feldspar growth (feldspars S2?). Large chloritic clots in many peg segs.  
 763.9-764m C(z) Intensely developed sericite shear plane dipping 50CA. Badly BROKEN zones at 763.9-764 5m  
 & 773-774.5m Low angle chloritic joint surfaces.  
 689.1-697.5m Ps(s,m\*t). Massive, pale grey psammite with a strong speckling of 1-2mm, black biotite clots.
- EOH @ 786.2 metres



### Appendix 5.3. Drill hole log of DDH 3355,

Pasminco northern leases, Silver Peak prospect (See cross section 31.00; Figure 4.42)

This drill hole was designed to test the Silver Peak Extended and the Potosi Orebody positions within the Lode Horizon in a position to the northeast of the main Potosi open cut. It crossed the Mine Sequence from the Sundown Group and into the Thackaringa Group.

HOLE No. 3355 LOGGED BY: T Webster PROSPECT: Silver Peak

0.0-1.5 No return.

1.5-23.8

cggGp sill,ser/wk shr Pg ser,q,c

Variably weathered, black pelite with abundant knots and clots of 1-3mm flame-shaped sillimanite bundles. Sillimanite is all retrogressed. Splotchy, skeletal, very coarse garnets occur in some bands and ragged 2-4mm skeletal garnets are ubiquitous. A single 60cm very fine-grained psammite band occurs at 4.2m. All pegmatite variably feruginised, fractured, oxidised and kaolinised.

1.9-3.6m Pser c

8.7-11.5 fggPg ser

12.8-14.2 Pc. Coarse, rounded clots of chlorite after cordierite?

15.2-16.7 brkn P (c) Minor chlorite clots on upper contact.

21.8-23.8 3 bands of P q within pelite.

23.8-79.2

cggGp sill, ser,

Medium grey pelite with abundant very coarse-grained, skeletal and ragged garnets. Many bands of black, white spotted pelite. Garnets are roughly arranged in bands within the pelite. 2-4mm, variably ragged, moderately sericitised fibrolite forms splotchy white knots throughout the interval. Knotty fibrolite texture due to interference of two foliations within pelite (S1 and S2?). Some 1-2m bands tend to more psammopelitic. 45-46.3m, strongly oxidised, goethitic, puggy and sheared fault.

ASYMMETRICALLY FOLDED THROUGHOUT INTERVAL, S2 FOLDS WITH 10cm WAVELENGTHS.

63.8-66.2 mgg Pg q

Band of garnet rich, siliceous pegmatite associated with a single 1m bands of medium grey, fine-grained psammite (on lower contact) Strongly broken, weakly feruginised in first 50cm.

79.2-102.6

cggGq mgg,d,fgg, b ((gah?))/fggGq bq, b/cggGp sill, ser

Variably siliceous, translucent, medium grey psammite. Two main types; first type is spotted by ovoid, skeletal, oval shaped garnets which are rimmed and impregnated by feldspar. These feldspar rimmed garnets give the rock a distinctive spotted appearance. Second type is a very fine-grained glassy psammite with variable, well rounded 2-3mm garnet and a dusting of fine biotite and possible gahnite. Psammite appears to be feldspar altered. Narrow bands of black, knotty pelite occur in some places. Interval is probably asymmetrically folded throughout.

90-94.4

fggGqe bq, cgg, mgg, (bs), (cp, po)

Very fine-grained, glassy grey psammite with common biotite speckling and common 0.5mm-2.5mm well rounded garnets. From 90-90.8m the psammite is rich in pink garnet, is strongly silicified by blue quartz and resembles an epidosite. It is relatively rich in very fine-grained chalcopyrite and pyrrhotite. Possible trace gahnite.

83.8-84.7 P (mgg)

102.6-113.5

cggGp ser/Gqe->Gq ((fgg))/P q

Moderately retrogressed, light to medium grey pelite with common 5mm ragged clots of fine-grained garnet. Also present are several patches of 1-3cm ragged garnets defining vague bands. A weak to moderate retrograde foliation is ubiquitous.

106.4-107.8m Gqe->Gq ((fgg)). Dark grey glassy psammite.

106.1m, 10cm green and cream banded epidosite.

107.8-109.8m Pq White, very coarse-grained, myrmekitic pegmatite. Intense silicification and weakly sheared. Developed in association with psammite band.

109.8-111.1m Gqe->Gq ((fgg)). Dark grey glassy psammite.

113.5-120.8 mod shr cggGp ser

Moderately sheared light to medium grey, retrogressed pelite with common clots of fine-grained garnet up to 4cm.

113 8-117m most intensely sheared and badly broken parallel to retrograde foliation.

120.8-132.9

mggGp sill, ser, bc

Distinctively biotite speckled (ragged 2-3mm clots), garnet spotted, medium grey pelite with common knotted to flame shaped, weakly retrogressed fibrolite bundles. Garnets are weakly skeletal but of very consistent grainsize and rounded. Biotite clots elongate parallel to foliation (S2?). Rare granular textured, fine-grained psammite bands. Knotted texture produced by interference of S1 and S2?

132.9-153.2

#### Sundown Group

fgg mggPGb->fggGq/Pg ser,q/mggGp ser

Interval of interbanded, variably potosi-like rock and variably garnetiferous pegmatite. A single interval of retrogressed, weakly sheared, medium grey pelite is present.

132.9-135.1m cggPg ser,q,c

135.1-138.1 fggGq bq->Pg Fine grained glassy grey psammite resembling fine-grained potosi.

138 1-140.4 cggPg ser,q/cggGp ser. Intensely silicified and sericitised (sugary) pegmatite with some rounded red garnets and a strongly developed, black pelite selvage.

140 4-144 fggGp ser. Finely foliated, schistose, medium grey pelite.

144-149.8 cggPgb bq/cggPg ser,q. Strongly developed medium blue grey potosi with 2m pegmatite band in the centre.

149.8-153 2 Pser, q,((cgg)),sph,((cp))/fggGip q Strongly silicified and sericitised pegmatite with an 80cm band of sericitic psammopelite in the centre. 1cm splash of sphalerite and minor, very fine-grained chalcopyrite in pegmatite in the last 40cm.

153.2 157.5

#### Broken Hill Group

fggGis (bq),(gl),(cp,po))

Black psammopelite with abundant fine-grained garnet and knotty, 2-4mm feldspar-clots. garnets tend to cluster together in places to form 2-5mm aggregates. Moderately developed, biotite defined schistosity. Interval in asymmetrically folded by 5-10cm folds. S1 undulose. Weakly tends to potosi in narrow zones.

155.5m 1cm wide galena stringer.

157.5-160.9

fggGq->Gqe/fggPGb->Gis

157 5-159.2 Interval of strongly siliceous, medium to dark grey psammite with broad bands of very fine pink garnet (epidosites?) which variably tends to potosi-like in texture.

159.2-160.6 Fine-grained garnet Potosi gneiss with 0.5cm bands of spotted psammopelite-like material.

160.9-164.4

Pl ser,mv,q,((cgg))

Intensely silicified and sericitised green feldspar lode pegmatite. Most green feldspar is intensely altered to grey feldspar with only small spots and cores preserved as green feldspar. Interval is moderately sheared forming a coarse anastomosing network of sericite and muscovite-filled fractures which wrap feldspars

164.4-170.3

fggPG bq->fggGq

170.6-174.1

fggPG bq,mgg/Pbq Very milky blue quartz-rich potosi with blue quartz pegmatite veining.

177.5-180

mggPGb fgg. Traces of mineralisation (gl,cp,py).

180-186.6

mggGis fgg,ser,bq,(mv)/Pl bq,ser,q,gah,gl,cp,py,sph/P q,ser

Interval of weakly developed spotted psammopelinite with medium grained garnets and clusters of fine-grained skeletal garnets. A strong, hairline sericite schistosity (after sillimanite) is developed throughout. 1-15cm bands of intensely silicified and sericitised pegmatite occur throughout.

181.6-182.2 minbq gah,gl,po,py,cp Strongly developed blue quartz mineralisation with coarse sulphides in 6cm white quartz vein at 182m.

184.3-185.7 Pl/minbq Band of very well mineralised green feldspar pegmatite with 12cm, very high grade sphalerite band on upper contact and coarse chalcopryrite and pyrrhotite mineralisation in following 20cm.

185.7-186.3 Gis->minbq

186.6-191.8

mggPG bq/fggGq ser->PG/mggGis

Interbanded interval of variably potosi-like rocks with occasional 1-5cm pegmatitic segregations and bands which resemble spotted psammopelinite. Strong to moderately developed, fine sericitic schistosity throughout mafic areas.

191.5-191.8 P ser,q with traces of sulphide.

191.8-200.2

mggGis->Gip/Pl ser,bq,q,(sph,gl,py,cp)

Moderately developed spotted psammopelinite with common, weakly lenticular (boudinaged) pegmatitic segregations (average 3-5cm) below 195.6m. Mineralisation is associated with most pegmatite stringers.

195.8-196 Pbq->minbq ser, c, py,cp,lo. Trace green feldspar preserved in intensely mineralised pegmatite.

196.4-197.3 Pl q,ser,(b)),((sph?)) Bands of variably silicified pegmatite with weak mineralisation and 15% psammopelinite.

197.3-197.6 Gis/minPl q,ser,(sph,py,lo). Bands of siliceous pegmatite in spotted psammopelinite with a single 6mm sphalerite stringer at 197.4m.

199-200m Gis q/Pl q,bq,ser,(gl,py,lo). Interbanded green feldspar lode pegmatite and spotted psammopelinite with a single 1.5cm, galena-rich stringer at 199.5m

200.2-235.2

P ser,bc,q

Massive white to creamy white pegmatite with broad zones which are rich in ragged clots of dark biotite and a moderately to weakly sheared upper contact.

200.2-201.1 mod shrPl ser. Moderately sheared and silicified pegmatite with a strong 'fish scale' texture produced by fine, anastomosing, weakly ferruginised shear planes which wrap eye-shaped feldspars. Most feldspars have weak green cores.

201.1-205. wk shr P q,ser. Weakly sheared light medium grey, translucent pegmatite with a fine anastomosing shear fabric which gives the interval weak to moderate 'fish scale' texture. The lower contact is transitional over a broad interval.

205-209 P ser,q,bc. Transition from silicified and weakly sheared to milky white sericitic and biotite-rich pegmatite.

213.7-215 P Coarsely myrmekitic

222-224.7 mod shr P q, ser. Moderately sheared and silicified, with anastomosing, 'fish-scale' texture. Sericitic planes are strongly silicified and saccharoidal in texture.

227-228.5 Pl q, ser. Coarse-grained with remnant green feldspar

235.2-246.2

fggGiq ser/mggGp ser,cgg

Interval of medium grey psammopelinite with many sillimanite (sericitised) and garnet-rich pelitic bands. Sillimanite is variable in texture from fine, fibrous foliae to 1-2mm wide, lenticular clots. The boundaries between pelite and psammopelinite can be transitional. Pelite is very rich in coarse sillimanite (sericite) foliae and clots, has medium to coarse, rounded garnets and tends to spotted psammopelinite in many places. Vague bands of psammopelinite with coarser garnets begin to resemble potosi in texture.

Asymmetric F3 (?) FOLDING of consistent style and orientation occurs throughout the interval. Wavelengths 10-15cm, rounded, tight hinges.

246.2-265.6

mgg-cggGis ser,q,((py))/minbq gah,ser,sph,gl,po,py,(lo)

Variably well developed medium grey spotted psammopelite with abundant rounded, 2-3mm garnets and a strong retrograde, sericite schistosity (after sillimanite). Three high grade bands of blue quartz-gahnite mineralisation occur between

254.2-265.6m. The first two have 6cm bands of weakly pebble textures sphalerite on their upper contact and the third has three 6-12cm bands. Minor disseminated mineralisation (mostly pyrite and trace chalcopyrite) occur throughout the interval. Garnets are all fine-grained and the interval is enriched in sillimanite (sericite) below  
261.1

246.2-247 fggGp q. Pale grey 'bleached' psammite. Strongly silicified with pink bands composed of very fine, silicified garnet.

254.2-255.5 HG minbq gah, sph,gl, py,po

260.6-261.1 HG minbq

264.9-265.6 HG minbq

265.6-282.6

fggGq ser/mggGp ser/mggGp->Gis/Pbq ser 40% 35% 25%

Sequence of interbanded fine-grained garnet psammite and sillimanite-rich (sericitised) garnet pelite. Bands of variable blue-quartz bearing pegmatite from 10cm to 35cm occur throughout the interval, mostly at pelite-psammite contacts. Psammite is light grey with wispy, hair like sillimanite foliae and a dusting of fine garnets. Pelite is generally dark grey to black, with variably 'knotty' sericitised sillimanite bundles and 2mm-6mm garnets. Pelite often tends to spotted psammopelite.

282.6-300

mgg fggG1 ser->PG

Medium grained garnet bearing quartzofeldspathic gneiss with a medium bluish grey colour and a moderately well developed schistosity defined by fine wispy foliae of sericitised sillimanite and biotite. Texture is quite homogeneous through interval and resembles fine-grained potosi.

1cm-12cm pegmatitic segregations are common. 0.5cm, coarse galena stringer at 296.55m. Ptygmatic folded pegs and isoclinal folds from 289m to end of interval.

Coarser, flames shaped sillimanite bundles from 291-293m

300-309.6

mggGip ser,cgg/fgg G1q ser 75% 25%

Similar to preceding interval (transitional) but with an increase in pelitic component. Interval is dominated by 5-50cm bands of pelite to psammopelite with abundant, coarse, flame shaped and lenticular bundles of sericitised fibrolite. Finer grained garnet bearing psammitic material (as in preceding interval) consists of 1cm to 5cm bands which decrease in size and abundance with depth. Open to tightly folded and ptygmatically folded pegmatite stringers occur throughout. Flame shaped nature of sericite bundles is due to interference of S1 and S2 crenulation-folding.

309.6-313.3

4.7

fggGq bq (ser)/Gp ser,(mgg) 85% 15%

Fine-grained, light milky bluish-grey psammite with a fine dusting of garnets and 0.5-2cm bands of dark, fibrolite-rich pelite (sericitised). Pelite bands become larger and more common to base of interval. Transitional unit between 4.7 and 4.5-4.6.

313.3-316.8

4.6

mggPg q,ser/cggGp ser 70% 30%

White silicified and sericitised pegmatite (very fine-grained saccharoidal) with clots and clusters of red garnets in patches throughout (especially associated with pelitic bands) Pelite occurs as black, fibrolite-rich selvages on pegmatites and as bands within a unit of fine-grained garnet psammite (as above) between

313.6-314.6m. Pelite is rich in very large bundles of sericitised fibrolite.

4.7-4.6 (4.5) contact.

316.8-321

#### Freyers Metasediment

fggGq/fggGp ser

Finely interlayered sequence of psammite and pelite. Psammite is light grey, pelite is black with large lenticular knots of sericitised fibrolite. Bands average 1-2cm.

321-337.5

fggGq bq/Pbq mgg

4.5

Unit of massive, dark grey to bluish, glassy psammites with common patches and vein-like occurrences of blue-quartz pegmatites. Traces of pyrite, pyrrhotite and chalcopyrite are common. Position of POTOSI MINERALISATION? Faint wisps of sillimanite and slivers of dark pelite occur in places Interval becomes less translucent, more granular and contains few blue quartz pegmatites below 332m.

337.5-341

fggGip ser

Medium grey, strongly schistose and sericite-rich psammopelite with common 1-2mm garnets occurring within 1-3mm wide, lenticular biotite selvages between retrogressed sillimanite foliae. Some 'knotty' feldspars and ine bands of psammite in places.

**341-353**

Gq (bq,fgg)/fggGp ser 65% 35%

Monotonous sequence of interbanded fine-grained psammite (similar to lower part of interval at 321m) and pelite with common, lenticular, 2-4mm wide retrogressed fibrolite bundles. The contacts between psammites and pelites are obscured by differentiation in many cases. Some blue quartz in psammite and larger blue quartz pegmatite veins begin to come in again at 351m.

**EOH @ 353m**

## Appendix 5.4 Typical Intersections of the Hangingwall Quartzofeldspathic Gneiss, Pasminco southern leases, section 340.

### Appendix 5.4A. DDH 7784.

A typical intersection of the Hangingwall Quartzofeldspathic Gneiss (intersected in the upper part of DDH No 7784, on Pasminco Mine Southern Leases Cross Section 340. This hole was collared to the northwest of the ore position, to intersect the MinSeq at depth. Logging by the author.

0-4.5

No Return

4.5-163.0 GG(c\*g,cOd,m)->PG/+-A(a,x,t,fg)

Homogeneously textured medium to light grey, coarsely gneissic granite gneiss which strongly resembles Potosi Gneiss throughout interval. 2-3cm long, lenticular white feldspar porphyroblasts are a major component of the felsic gneissosity. Dark biotite defines a distinct foliation and medium to coarse, skeletal to ragged garnets (strongly biotite altered) are common throughout. Fine wisps of white fibrolite in places. Broken in first 30m (oxidised zone). S2 gneissosity dips 46CA at 21.3m, 51CA at 57m, 31CA at 93.9m, 22CA at 111.6m, 22CA at 151.6m. GG weakly to moderately matrix oxidised to 15.3m and contains goethitic fractures to 34.3m.

70.6-70.75m, 91.9-92.1m, 109.6-111.4m, 114.8-115.3m.

Most are moderately chloritic and biotitic, especially at margins. All are finely banded by a amphibole-chlorite foliation which cross-cuts the gneissosity in the granite gneiss (later). Minor bands of biotite-garnet rock at contacts and individually in amphibolite zones. Garnets in granite gneiss are totally altered to biotite in amphibolite zones. S3? dips 22CA at 114.8m in amphibolite (truncated gneissosity in granite gneiss).

A(a,x,t,fg) bands A(a,x,t,fg) bands at 67-67.4m, 67.7-68m, 68.5-68.7m,

163.0-182.6 wk-str shd GG(z,x,t,+-cg)/C(z,x)

Weakly to strongly developed shear zone within the granite gneiss which has a central core of intense shearing and progressively less sheared margins from centre to edges.

163-164.2m. str shd GG(c\*g,t,z,+-x)->C(z,t,x).

Knifedge upper contact of shearing truncates S2 gneissosity in Granite Gneiss. Shear foliation dips 25CA.

164.2-165.3m. mod-str shd Peg(s,z). Intensely sheared pegmatite.

165.3-167.6m. brkn C(z,x). Intense plane of retrograde shearing composed of fine, intensely schistose sericite and chlorite. Foliation dips 23CA at 166.2m. Some reddish (haematitic?) alteration at 166.2m. Puggy and broken along some planes of foliation (later brittle movement)

167.6-179.1m. str shd GG(z,x,cOd,t). Intensely sheared granite gneiss with many preserved feldspars as augen and some biotitic selvages. Foliation dips 27CA.

179.1-181.1m. mod shd GG.

181.1-182.6m. wk shd GG

182.6-247.5 GG(c\*g,cOd,t,m)->PG/+-A(a,x,t,fg,cg)

Homogeneously textured medium to dark grey, coarsely gneissic granite gneiss which strongly resembles Potosi Gneiss throughout interval. 2-3cm long, lenticular white feldspar porphyroblasts are a major component of the felsic gneissosity. Dark biotite defines a distinct foliation and medium to coarse, skeletal to ragged garnets (strongly biotite altered) are common throughout. Fine wisps and fine lenticular bundles of white fibrolite in places. Interval becomes progressively more mafic, garnet-rich and richer in fibrolite with depth and is slightly more mafic than the interval at 4.5m. S2 dips 36CA at 187.5m, 36CA at 201.7m.

200.6-201.6m and 202.5-203.9m. Peg(s,z). Two bands of coarse-grained pegmatite.

211.6-214.4m. GG(+/-m,+-fg)

Strongly leucocratic, translucent white to pale grey 'Granite Gneiss' variant (aplitic?). 0.5-1mm wide wisps of fibrolite form a weak foliation dipping 45CA at 213.4m

A(a,c,t,fg,c\*g).

A(a,c,t,fg,c\*g). Bands of fine-grained, variably biotitic, chloritic and coarse garnet-bearing amphibolite at 217.9-218.6m, 222.2-222.9m, 223.4-223.7m 10cm band of t-c\*g rock at 216.7m. Coarse garnets are much more common than in preceding intervals.

247.5-255.7 GG(c\*g,m,t)->PG/leucGG(d)/A(x,a,t,c\*g) 60% 10% 30%

Composed mainly of medium to coarse-grained, medium grey, translucent granite gneiss, which strongly tends to Potosi Gneiss. Garnets are common, but much less so than preceding intervals. No pronounced felsic gneissosity is present and the matrix tends to massive. White, hair-like to horse tailed, fine fibrolite foliae are common. Bands of leucocratic granite gneiss occur in places, generally around 2-3cm. A single 12cm band with feldspar-rimmed ovoid mafic clots (as seen commonly in Suite 5 metasediments) occurs near top of interval. Band of brittle chloritic fracturing parallel to CA between 252.3m and 253.6m. S1 dips 42CA at 250.1m.

A(a,t,x,c\*g,fg). A(a,t,x,c\*g,fg). Bands of variably biotitic and chloritic amphibolite at

255.7-256m, 257.1-257.6m, 257.8-258m, 258.2-258.6m.

leucGG(d,m\*g,m,+/-c\*g)

leucGG(d,m\*g,m,+/-c\*g)

Pale translucent grey leucocratic 'granite gneiss' variant (contact phase) with common, hairline to horsetailed bundles of very fine fibrolite that define a weak foliation (S1?). Coarse lenticular splotches of feldspathic and pegmatitic segregations contain clusters of mafic minerals in their cores. Lenses are parallel to weak foliation.

18cm band of biotite-garnet rock at 264m and a 20cm band on lower contact.

273 0- 314.8 cPe(fg,t,+/-m\*g)/Pe(fg,t,+/-m\*g) 60%, 40%

Black biotite-rich pelite which is rich in 2-7cm wide pegmatite segregations between 273-287.3m. Garnets are sparse and fibrolite is only present as occasional fine hairlike to lenticular bundles. S1 dips 52CA at 277.7m, 52CA at 290.5m, 49CA at 306.7m.. F3 FOLD with 4cm wavelength dips 46CA at 291.4m (folds S1)

The pelite becomes progressively more psammopelitic below 306.2m and is medium grey in colour. Lower contact is transitional and taken as the top of the first psammitic band.

302-302.5m and 307.8-308.9m. Peg(u,z,+/-x)po,cp/Pe.

Two zones of blue quartz pegmatite with varying amounts of pyrrhotite and lesser chalcopyrite.

## Appendix 5.4B. DDH No 7835

A typical intersection of the Hangingwall Quartzofeldspathic Gneiss (intersected in the upper part of DDH No 7835, on Pasminco Mine Southern Leases Cross Section 340 (HQ to 198.4). This hole was collared to the west of the ore position in the to intersect the MinSeq at depth. Logging by the author. GG = Hangingwall Quartzofeldspathic Gneiss.

0.0-6.9 no return no return

6.9 - 523.4 GG (c\*g,t,d)

Coarsely gneissic granite gneiss which is variably felsic and biotitic. Biotite tends to form ragged clots and elongate ragged lenses (after garnet?). Variably Potosi-like in places. Garnets clots become better preserved with depth and the rock takes on a strong Potosi-like appearance. Fibrolite becomes common towards base of the interval. S1 dips 32CA

22.6m & 37m, 25-20CA

133.5m, 30CA

223m & 280m,

341m 35-40CA,

500-523.4m. 30CA

Moderately matrix oxidised and chloritic. Puggy and milled from 16-18 metres.

26.5-32.6 A (x,t,c\*g)



Zone of four fine grained, chloritic and biotitic amphibolites which post-date S1 in granite gneiss but which have strong biotitic alteration associated with coarse ragged garnet and some fibrolite (pre S2?). A fine biotite and chlorite (after amphibole) foliation (S2?) occurs within them.

44.6-47.2 Zone of 3 narrow fine-grained amphibolites which cross cut S1 in GG but have a fine garnet-amphibole foliation. 2m GG in middle.

146-187.8. C(z,t,d)->shdGG

Intensely sheared granite gneiss with abundant flattened biotite lenticles (after biotite clots). Intensely schistose between.

155-159.6 Badly broken 146-148m, (15-25CA).

155-159m. Chlorite and pyrite on fractures

224.1-225.8. brkn A(x,t,fgg)/GG.

Two narrow bands of chloritic, finely foliated amphibolite with 80cm of broken, moderately foliar GG between.

241.8-243.8 C(x,z,t)

Intensely developed chlorite sericite schist zone with zone if weakly developed chloritisation of GG around margins (chlorite after biotite). Possible Delamerian structure? Clayey sericite pug

Peg (s,z,+/-d)

Metasomatically altered, pale translucent grey to white pegmatite. Broken zone on upper contact.

337.5-337.9 A(x,t,+/-fgg)

Fine grained, finely foliated amphibolite.

364 4-367.8. A(x,t,+/-fgg)/GG->PG(c\*g).

4 bands of variably garnet altered, fine-grained amphibolite ranging from 4cm to 12cm with GG in between.

367.8-380. GG (c\*g,t)->PG/Peg (z,vd).

Zone of the GG in which a cluster of ragged, pale orange feldspar-bearing pegmatite is developed. Greatest density is best developed. Greatest thickness.

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## APPENDIX 6. STRUCTURAL METHODS

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### A6.1. INTRODUCTION.

The techniques used throughout this research project are those typically used in high-grade gneiss terrains (e.g. Hobbs et al, 1976; Passchier et al, 1990). To the author's knowledge, such techniques have rarely, if ever, been applied to an ore deposit study in this manner. The following sections outline the most important features of the mineralised system and Mine Sequence that have been recorded during the study.

### A6.2. MAPPING OF LITHOLOGIES.

A tried and tested way of determining the structure of a high-grade gneiss terrain is to map lithologies in detail. The orebodies, their distinctive companion lithologies and the internal gangue and textural variations within the sulphide silicate carbonate units that comprise the orebodies all provide enough variation in the mineralised system to provide mappable features. These elements of the mineralised system provide detailed marker units within the Broken Hill Group gneisses and schists that can be used as marker horizons to elucidate the structure of the mining field and the orebodies themselves

Interpretation of the distribution of distinctive companion lithologies (garnet quartzite, blue quartz-garnet-gahnite rocks, spotted psammopelite), pegmatite units and characteristic stratigraphic markers (Potosi type gneiss, amphibolite, calc-silicate horizons, banded iron formation, magnetite-bearing pelite) allows the Lode Succession (see Chapter 4) , the host sequence of the orebodies, to be characterised and defined for the first time.

The advantage of utilising and comprehensively reinterpreting the geology of underground mine level mapping is that it provides a stacked series of lithological and form surface maps that reveal the changing geometries of fold structures, shears, faults and folds with depth. Stacked series of geological form surface and lithological maps in orebodies in high grade gneiss terrains provide a "third dimensional" view that allows structures to be traced down plunge in a manner that would not be possible away from the mines.

The lithological contacts that were plotted on map sheets include; the garnet quartzite, lode pegmatite's, orebody contacts, rhodonite-bustamite bodies within mineralisation, the contacts of zones of low grade siliceous mineralisation / blue quartz-gahnite-garnet horizons, sericite-biotite-quartz rocks and zones of chlorite-biotite (+/- pug) fracturing. These contacts were adequate to define the detailed stratification of the Garnet Quartzite Horizon, which extends from the upper contact of 2L to the upper contact of the BL Horizon (including 'C Lode'). No attempt has been made to differentiate between psammite, psammopelite or pelite during this work. The trace of quartz-muscovite-biotite shear zones and later chloritic, puggy or veined faults has been inferred/included where data are available.

While interpreting the existing mapping and undertaking mapping as part of this project, the following features of the mineralisation and lode rocks have been a major focus (see following table).

<b>Orebody Contacts</b>	All orebodies, especially 3L & 2L, have very sharp contact with surrounding rocks (Andrews 1922; Gustafson 1939; Webster 1994). Their boundaries are not usually transitional or grade- defined but are distinct geological contacts.
<b>Gangue type distribution</b>	mapping of gangue type distribution
<b>Gangue type textural variations</b>	mapping of gangue types, textures & their distribution
<b>Sulphide textures &amp; textural variation distribution of sulphide veining &amp; its characteristics.</b>	Mapping of sulphide types & textural variations within orebodies
<b>Mapping of the distribution of quartz veining styles</b>	Provides information about the structural history of the ore. including blue quartz, white quartz & clear quartz veining.
<b>Mapping of alteration zones in orebody wall rocks</b>	Especially North Mine where the zones transgress form surface trends in metasediments
<b>The distribution of major lode rock types</b>	(Garnet quartzite, spotted psammopelite), pegmatite units, & characteristic stratigraphic markers (potosi gneiss, amphibolite, calc- silicate ellipsoid zones, 'banded iron formations & magnetite-bearing pelite units.
<b>Distribution of veining</b>	Define zone of brittle deformation.

Backs mapping was carried out in the style required for true form surface mapping.

#### **A6.2.1. Mapping of Marker Units.**

##### *Outcrop mapping*

Direct observations of outcrop made in

1. Underground backs mapping

2. Wall mapping
3. Face mapping
4. Remaining surface exposures (outcrop/ cutting / open cut faces)
5. Diamond core (?)

There are a limited number of available faces available, so to gain a picture of the entire deposit, the work of others had to be extensively used (existing underground mapping)

### ***Distinct ore lenses***

Important on a mine scale and that are the most important features for structural interpretation through the field. Identifiable by (much work in the past has been done on this aspect and it is discussed in other chapters (orebody stratigraphy).

1. stratigraphic position
2. gangue mineralogy
3. metal ratios (?)

### ***Lode rock units***

1. Garnet Quartzite Horizon
2. Blue quartz rocks

### ***Elements of the mine stratigraphy***

1. Potosi Gneiss
2. Amphibolites
3. Magnetic Pelites
4. Calc silicate horizons

### ***Marker horizons within orebodies***

1. rhodonite/bustamite
2. calcite-fluorite bands (?)
3. massive sulphide units
4. fluorite rich zones
5. banded ore
6. metasediment layers and interdigitations

### *Overprinting & intrusive relationships (what overprints what)*

Observation of ;

1. Mineralogical zonations,
2. Sulphide zonations,
3. Gangue/sulphide grainsize variations
4. Mineral suites
5. sulphide/gangue texture variations,
6. lithological variation
7. overprinting relationships within the orebodies (generations of sulphide veining, gangue mineral growth,
8. pegmatite generations
9. dolerite dykes

### **A6.3. FORM SURFACE MAPPING AND FORM SURFACE EXTRAPOLATION**

Form surface mapping is a common method for determining the structure of high-grade terranes (e.g. Hobbs et al., 1976) and has been utilised extensively in this project. Form surface mapping “records the layers that are too thin to record on the map and consists of simply representing the trace of any penetrative surface on the map” (Hobbs et al 1976).

Form surface mapping is a useful technique to define the geometry of structures in monotonous gneissic sequences. During this project, the technique was extended to reinterpreting existing map data from (often) long-abandoned underground workings. It was found that by extrapolating form surface trends between exposures in adjacent mapped workings, a detailed picture of structural trends and truncations of trends could be built up on successive mine levels. This process, known as “form surface extrapolation” allows highly accurate forms surface maps to be compiled for mine levels. Complex and geometrically variable fold and shear structures and the varying geometry of lithological units within the wall rocks can be traced from level to level through the mines and thereby through the whole mining field. Stacked sequences of such plans, referenced to the same mine grid, provide a pseudo three-dimensional means of observing the changing geometry of complex folds, shears and lithological units. Structures can be followed down-plunge and down-dip through the gneissic packages.

Correlation of lithological marker units provided a control and a support for the form surface trends identified. Careful interpretation of lithological marker units within the

gneisses, lode rocks and within the orebodies augments the information derived from form surface mapping and form surface extrapolation. The complex geometries of lode rocks and key marker units is defined and the variations in these units with increasing depth is revealed in successive maps.

The simple techniques described above were also found to be equally applicable to the rocks of the orebodies themselves. The orebodies possess a variety of banding textures, readily distinguishable gangue mineral zones and sulphide veining of a variety of types and distinctive mineralogical complement. Small pegmatite intrusives and late dolerite dykes can also reveal details of the effects of deformation within the orebodies if mapped carefully, as can sulphide veining of various geometries and locations. Banded ores, gangue and sulphide-defined marker units in the orebodies can be utilised to compile form surface maps (with detailed lithological mapping) in mineralised rocks just the same as in surrounding wall rocks.

The part of this project that is least typical of a structural investigation of a high grade gneiss terrain because it is carried over many different levels of a mine, with outcrops one atop the other. There is an element of 3D observation available in this investigation as the same lithological units, fold, shear and fault and structures can be observed at successive depths as they carry through the mine levels to *depth, rather than on a single surface*.

Mapped planar features typically mapped underground as form surfaces include bedding, pegmatite segregations developed at pelite-psammite bed contacts, transposed bedding/pegmatitic segregations, amphibolite units, calc-silicate units, attenuated amphibolite & calc-silicates.

High grade shears, fold structures and structural trends that may not be revealed by interpretative, drill hole based cross sections may be recorded in detail in production oriented geological mapping of development drive backs even though they may not be apparent while actually mapping. Such mapping, while carried out in narrow strips of underground development can be utilised at Broken Hill in a similar way to outcrop mapping and form surface mapping in any structurally complex high-grade terrane. There is an added advantage in using underground mapping in this way, in that underground development provides detailed outcrop maps at successively deeper levels in the same area where true outcrops only reveal the structure on one plane (the

surface) - such as is described in Hobbs et al (1976). In deep underground mines such as Broken Hill, structural interpretations can be carried out in the horizontal plane every 30 to 40 metres down to depths of 2 kilometres in the vicinity of the orebodies. In areas of stope mapping, such as the Pasminco Mine, it would be possible to compile detailed structural maps every 2.4 metres of vertical depth as stope mapping was done at these densities. While this density of data is available, it has not been attempted during the current research.

At Broken Hill, form surfaces recorded by geologists in drive and stope backs (and occasionally stope walls), can represent bedding, transposed bedding, metamorphic layering or structural foliations. In many instances, particularly in early mapping, there was no record made of what type of geological feature the mapped form surfaces represented so it is often difficult to determine whether bedding, gneissosity, transposed bedding or a shear fabric was being represented (though accompanying reports suggest that the observers considered these surfaces to represent bedding), particularly in zones of high grade shearing and transposition. However, general form surface trends are apparent and obvious planes in which the form surfaces are truncated at high angle by adjacent zones can reveal shear planes, parasitic folds, cross folding, undulations in fold plunges, successive generations of shearing and so forth.

An added bonus for the application of form surface interpretation at Broken Hill is that all mapping took place in a horizontal plane (drive backs) and so there is no topography induced distortion as can happen in undulating surface maps.

One modification of more typical form surface mapping that has been used here is that form surfaces have been extrapolated beyond the actual underground mapped drives ("outcrops") along apparent trends revealed in the factual mapping. This technique is particularly applicable where there are grid-like networks of parallel development drives at the same relative level in the mine and in which obvious form surface trends can be extrapolated between the opening to infill the blank areas. Thus, an interpretative style of form surface structural map can be compiled which reveal details of the structure that would otherwise not be visible. High-grade shear zones and zones of transposition are most readily revealed by this technique.

The applicability of form surface mapping and interpretation within the mineralisation at Broken Hill also reveals its internal structure, as has been demonstrated by Webster



(1993; 1994). Using existing mapping, new mapping, form surface mapping and form surface extrapolation in both backs and stope panel and drive walls I demonstrated that the internal structure and structural history of the 2L orebody in the Pasminco Mine was recorded in carbonate-silicate-sulphide banding, sulphide-silicate-carbonate gangue variations and variation in sulphide textures. I also showed that the 2L orebody was mostly conformable with the surrounding rocks. Webster's (1993; 1994) approach has been developed further during the current research. The approach developed in Webster (1993; 1994) has been further developed in this thesis.

#### **A6.3.1. Fold geometry.**

Form surface maps allow the accurate definition of fold geometries in the orebodies and wall rocks. Folding of varying style, wavelength and intensity occurs within all orebodies and adjacent rocks throughout the length of the deposit. The style of folding is variable and changes from region to region through the deposit. Three clearly distinct and overprinting generations of folding are recognized.

1. Early (prograde) folds that occur throughout the deposit and are associated with the peak of metamorphism. These early folds predate the high grade shearing and are the most significant influence on orebody geometry within the mining field.
2. Early retrograde folds that are localised and associated with narrow, intense planar shear zones and,
3. Later folds that are intensely localised and associated with late retrograde shearing and faulting, and possibly associated with the warping of the whole Broken Hill region. Key examples are the 'Menindee Road folds'.

The interlimb angle of individual orebody-scale folds is difficult to determine because there has been significant (often extreme) modifications of the limbs by post-fold shearing and attenuation. However, examples of reasonably preserved folds are seen in the Block 14, South and Pasminco mines within 2 Lens and 3 Lens. Lithological mapping shows that the orebodies (such as A Lode Lower) transgress the strike of the early fold hinges and do not plunge parallel to fold axes. Instead, they have an independent plunging geometry.

Folding of varying style, wavelength and intensity occur within all orebodies throughout the length of the deposit. The styles of folding are variable and change from region to region.

^  
Folds are of three generations;

1. Early asymmetric south verging throughout the deposit,
2. Later – tight to isoclinal and associated with shear zones and,
3. Final, broad amplitude cross folding and warping of the WSG basement, localised in association with fault systems. Refolding of the mining field especially focussed around the Menindee Road area. Some metre-scale folds (e.g. Burrell Bend fold).

There is a distinct zone in the region of the boundary between the south mine and the Pasminco mine, where the folds appear to have been severely affected by attenuation and the original fold geometry is so severely modified that little can be determined except that there was an antiform and a synform

#### **A6.3.2. High-grade Shears.**

Form surface maps of mine levels reveal the location and orientation of intense planar shears. High grade shears that might otherwise go unnoticed in a monotonous gneiss sequence may be revealed by sudden changes in the orientation of foliation/banding/bedding, truncation of a particular zone of banding, truncation of domains of folded banding and truncation and/or attenuation of lithological marker units (including segments of the orebodies). Widespread compilation of information at similar relative levels throughout the mined area allowed the pattern of the anastomosing array of high-grade shear that occur throughout the mining field to be identified and defined accurately. The model developed is significantly different from that of most previous workers. Form surface maps reveal a relatively common relationship between fold hinge zones and planes of high-grade shearing. Fold hinges are seen to be well-preserved in general, while the fold limbs are the locus of much of the high grade shearing.

#### **A6.4. FEATURES WITHIN THE OREBODIES THAT RELATE TO DEFORMATION.**

The metasedimentary sequence that immediately surrounds the BH orebodies contains many distinctive and characteristic marker units that can assist in the definition of the structure of these rocks. So do the orebodies. The mapping techniques described above were found to be equally applicable to the rocks of the orebodies, which possess a wide variety of banding textures, readily distinguishable gangue mineral zones, sulphide veining and small intrusive bodies. Gangue mineral textural variations (especially rhodonite and related species) also provided information about the metamorphic history of the rocks. Key marker units mapped within the orebodies include,

1. rhodonite/bustamite layers and zones,
2. calcite (zones of varying density in sulphide rock), fluorite & apatite zones & bands,
3. fluorite rich zones,
4. massive sulphide units,
5. banded sulphide ore,
6. metasediment layers that interdigitate with the ore lenses and lode rock units,

Later intrusives can also reveal fold geometries formed during late deformations and be overprinted by sulphide veining and alteration associated with late tectonic and metamorphic events. Thus they are applicable when defining the effects of later deformations. Key examples are,

1. early pegmatite intrusions
2. dolerite dykes.

Correlation of lithological marker units provided a control and a support for the form surface trends identified by form surface mapping, just as described above. The information that can be recorded within the orebodies is analogous to that documented in the wall and lode rocks.

##### **A6.4.1. Timing of deformational and metamorphic events in orebodies**

In high-grade gneiss terranes, "sequences of intrusion" into high-grade rocks form much of the basis for the relative timing of deformational events (Passchier et al, 1990). In the case of the Broken Hill orebodies, while pegmatite and dyke intrusion can be

used to provide relative dates on some events, it is the relative timing of gangue mineral textures, new gangue mineral species, quartz-hedenbergite veining (amongst others) and sulphide veining and mobilised ore types that fulfils this role in the orebodies and immediate wall rocks. The principles are the same.

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## APPENDIX 7.

# LEASE GEOMETRY CONTROLS THE STREET LAYOUT OF THE CITY.

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The most prominent manganiferous and ironstone outcrops of the "broken hill" were the first part of the hill to be pegged and the linear trend of the outcrop and ridge dictated the orientation and placement of the original mining leases. Therefore, the early prospectors recognised the strike of the manganiferous rocks (the 'line of the lode').

The mining field now lies in the centre of the urban area of the City of Broken Hill but it is the location of the Line of Lode and the leases pegged over it that controlled where and how the city developed. In the days before cars, most people walked to work. In a mining town, where most work was on the mines, people tended to settle as close to the mines as possible.

Apart from mine officials, people were generally discouraged from living on mining leases - partly because there could be no freehold title to any housing they may build and the leaseholder could evict them at any time, without compensation. Therefore, the initial scattered settlement at Broken Hill grew up on the open flat saltbush plain at the northwestern foot of the broken hill (Solomon, 1988). The original street of this settlement survives as Delamore St, named for the publican of the Bonanza Hotel, first hostelry of the town but followed soon after by the Silver King Hotel, the immediate successor of which is still there.

The original square 50-acre mining leased pegged by Rasp and his partners were placed carefully to ensure that the linear black outcrop of the lode was in dead centre. The line of these leases followed the strike of the outcropping lode at the crest of the Broken Hill and the lower, linear ridge to its northeast and southwest. It is the orientation of these leases that set the pattern for the future development of the settlement, which became the city.

The streets were surveyed officially in 1886 and the orientation of the main northeast southwest streets, such as Argent, Crystal, Blende, Beryl and Wolfram streets

paralleled the lease boundaries. In typical orderly fashion, the east-west streets were set up at right angles to the main northeast-southwest streets.

The main arterial road to Wilcannia and Sydney passes through Hancey's Gap, which lies between Colt Ridge and Lord's Hill, a corridor that follows the Globe Vauxhall Shear Zone between the main mass of the Sundown Group metasediments and the Hangingwall Quartzofeldspathic Gneiss.

Geology has controlled the placement and orientation of the mining leases and the leases have influenced the orientation and placement of the streets of the growing city. Clearly, Broken Hill is a city that is heavily influenced by its geology.